Journal of Machine Engineering, Vol. 16, No. 4, 2016

Received: *20 January 2016* / Accepted: *17 October 2016* / Published online: *09 December 2016*

simulation-based optimisation, optimisation criteria,
controller parameterisation,
time and frequency domain

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COMBINATION OF CRITERIA FOR CONTROLLER PARAMETERISATION IN THE TIME AND FREQUENCY DOMAIN BY SIMULATION-BASED OPTIMISATION

The position controller cascade is widely used in standard industrial controllers. Its controller parameterisation is commonly performed by either applying basic tuning rules or by carrying out not comprehensible design automatisms. In this paper an alternative approach to parameterise the cascade in one step is presented. It bases on established methods within the field of optimisation research – specifically the so-called "simulation-based optimisation" (SBO), which can also handle non-linear models and various constrains. Own research showed, that criteria in the time domain as well as in the frequency domain are suitable optimisation criteria. However, both types have individual advantages and disadvantages. Therefore, in this research, selected representatives from both types were combined as new multi-objective optimisation criteria and investigated according to their performance. Investigations were performed for a test rig model (third order transfer function plus dead time and friction). The paper presents fundamentals of the SBO and a description of the optimisation criteria, obtained results as well as their verification on the test rig. Also, the derived controller parameterisations are compared to the integrated tuning automatism.

1. INTRODUCTION

The application of simulation-based optimisation (SBO) for controller parameterisation offers various advantages over conventional approaches (e.g. the use of standard tuning rules like the Ziegler-Nichols method) [7],[8]. This includes the possibility of considering non-linear systems accurately and the ability of an easy definition of optimisation criteria and various constraints, as further stated in chapter 2.

Today, many software systems (e.g. the MATLAB® Optimisation toolbox) support this type of optimisation also for controller parameterisation. However, the influence of the optimisation criteria on the derived results and therewith on the controllers' achievable

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performance is not well investigated until today. One reason for that is the large number of existing evaluation criteria, such as the integral of absolute error (IAE), the bandwidth (BW) of the closed loop system and many more [1],[2],[13],[18]. Generally, these can be divided into time criteria and frequency criteria with both comprising different advantages and disadvantages as displayed in Table 1.

Table 1. Advantages and disadvantages of optimisation by time and frequency domain [7],[8],[9]

Time domain	Frequency domain
+ depiction of benchmark values like IAE, rise time and settling time - dependency on specific test signal - stability assertion only based on specific test signal by reference to stated benchmark values	+ independent from test signal + stability quantifiable e.g. on the basis of the phase margin - insufficient reproduction of friction and saturation

The established criteria are mainly used to assess existing controller settings and not yet to find the best controller parameterisation. In former research both types of criteria were already evaluated separately.

Based on the found conclusions, a combined approach is evaluated in this paper with respect to the suitability as optimisation criteria for the SBO under various constraints, also considering the impact of a velocity setpoint filter (VSF). A self-developed application was used as optimiser due to the freedom of adaptability, the transparency and the performance of the software system.

The structure of the used simulation model is introduced in chapter 3, followed by a description of the applied system design and controller structures in chapter 4. Chapter 5 gives an insight into the investigated criteria, the used constraints and the applied evaluation methodology. The results are presented in chapter 6 and analysed according to the rise and settling time and the IAE of the step responses to make them comparable with former research. Since these criteria are well known they are easy to interpret. Subsequently the results are verified on a test rig. To conclude the paper, a final evaluation of the investigated time and frequency criteria as well as an outlook are given in chapter 7.

2. BASICS OF SIMULATION-BASED OPTIMISATION

SBO is a process of finding the global extremum of an objective function in a defined search space, which is achieved through coupling the simulation of the system to be optimised with a fitness evaluation and an optimiser. The so called fitness value is calculated by the evaluator and consists of the assigned values of the optimisation criteria and the penalty values for violating constraints [4].

The optimisation done in this paper uses a hybrid optimiser, a combination of the Particle-Swarm-Optimisation (PSO) and the Nelder-Mead optimisation (NM), to minimise the fitness value of the Simulink® model illustrated in chapter 3. Generally, the PSO is a so called metaheuristic [6], because it makes no or only a few assumptions on the investigated optimisation problem. The basic principle of the PSO is the simulation of the movement of a swarm of objects (e.g. birds or fish) by trying to find the best solution. The NM algorithm (or simplex method), which was originally presented in [14], uses a geometric structure, the simplex, with n +1 points in the search space with the dimension n. So for example if n = 2 then the simplex is a triangle. By modifying the simplex according to defined rules the algorithm tries to converge the structure to the global minimum. By combining the PSO with the NM a significant performance improvement could be obtained [15].

In general, in the first step the optimiser initialises a proposed solution and sends it to the simulator, which calculates the respective fitness value and sends this back to the optimiser. It responds by sending a new, likely better solution proposal back. This cycle continues for a defined amount of runs or until the target value is reached (Fig. 1). Because of the limited space, for the description of the detailed working principle of the hybrid optimiser it is referenced to [15].

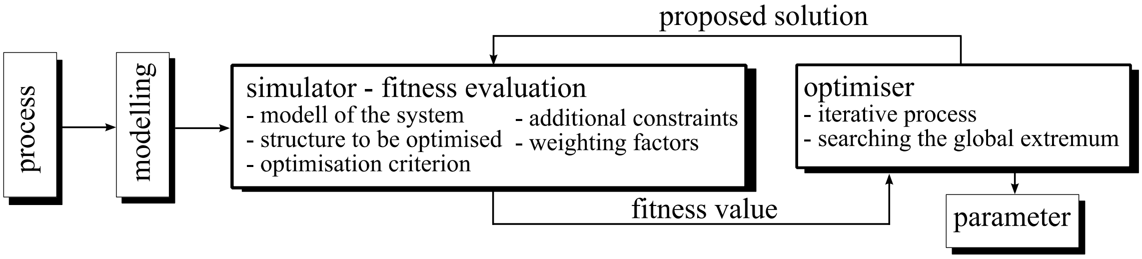

Fig. 1. Schematic loop of optimiser and simulator to find controller parameters

3. USED SIMULATION MODEL

In the presented case the simulation model was designed in MATLAB® Simulink®, operating in a step time of 125 μs to align the simulation to the test rig detailed in chapter 4.

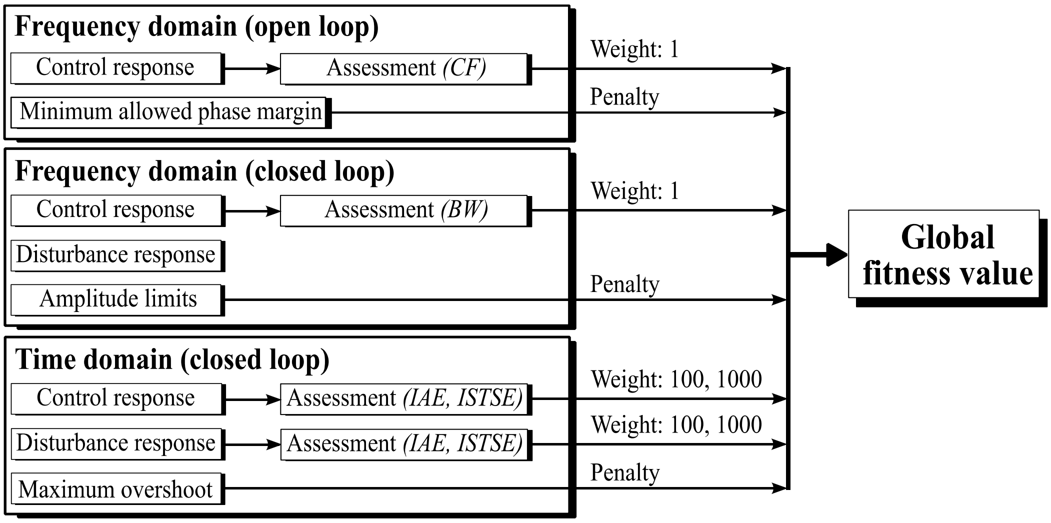

Fig. 2. Simulation model for the calculation of the fitness value

It calculates and evaluates the discrete fitness values of three individual control loops (frequency domain in open and closed loop, time domain) and the respective penalties for violating constraints simultaneously (Fig. 2). Closed loop variants are further subdivided into a setpoint response and a disturbance response each. The fitness values of the sub-model are multiplied with an assigned weighting factor to ensure a balanced impact on the results and subsequently cumulated to compose the global fitness value.

4. TEST SYSTEM DESCRIPTION

For the evaluation a model of the test rig shown in Fig. 3 was used. It is equipped with a SIEMENS motion controller SIMOTION D445® and SINAMICS® drives (clutch is open). The motion controller is sampled with 500 μs and the drive components with 125 μs [7].

Forming the core of the simulation, this experimental set-up is modelled as a two-mass-system with friction [10] as shown in Fig. 4.

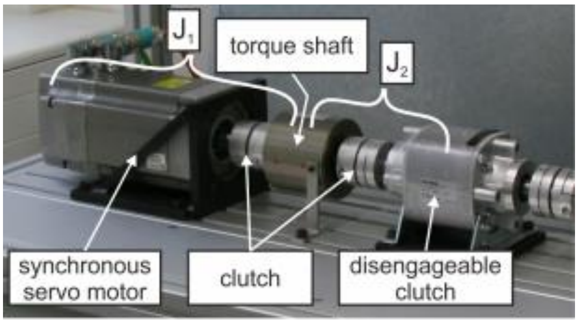

Fig. 3. Used test rig with known mechanical parameters

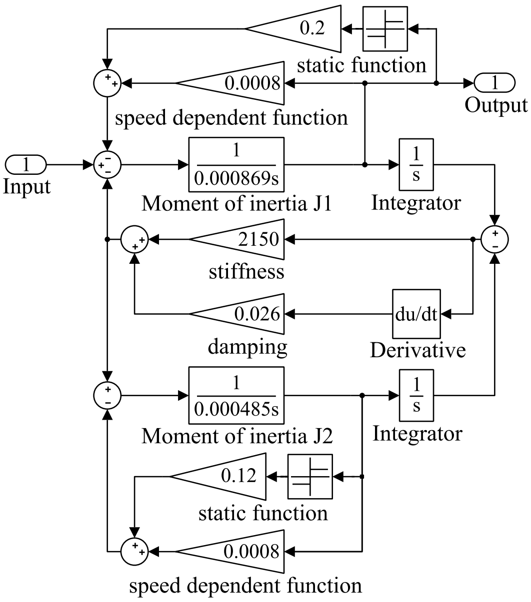

Fig. 4. Two-mass-system model of the test rig with friction [10]

The applied control loop is modelled using continuous transfer functions. The input signals run through a PT_1 VSF before traversing a PI speed controller, a current setpoint filter, a PT_2 closed current control loop, a transport delay and the above explained two-mass-system with friction, as seen in Fig. 5. Both, the PI speed controller with the parameters K_p and T_n and optionally the VSF with the parameter *T_DSWF* are subjects of the optimisation with the other variables set according to former research [7],[8] to keep the results comparable. In the time domain the model is receiving either the setpoint step (Δn=50 rpm, t=0.2 s), or the disturbance step (Δn=0.5 rpm, t=0.2 s) as input. The corresponding step response is returned as output.

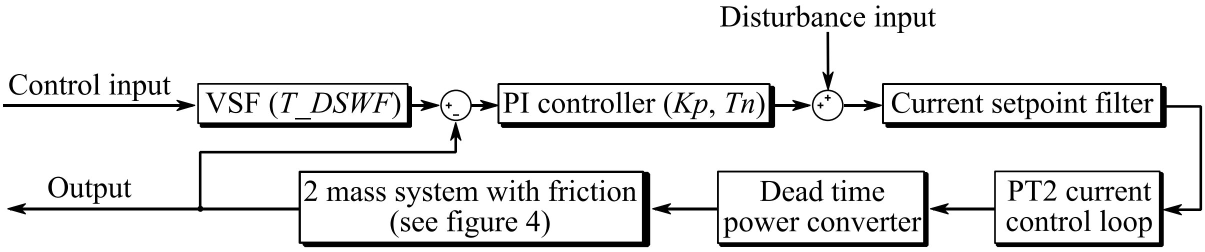

Fig. 5. Modelled control loop with filter, controller and controlled system

In the frequency domain, a pseudorandom bit stream (PRBS) signal is used as input, a binary signal which is utilised as a reproducible alternative to white noise in control engineering [20]. This paper uses a 13-bit-signal, alternating from -1 to +1, providing 8191 discrete states [10]. Therewith a frequency range up to 2000 Hz can be investigated.

5. INVESTIGATED CRITERIA

The consequences of using two different optimisation criteria for time domain and frequency domain each was examined with regard to their results in the SBO, as well as the impact of three optional constraints.

5.1. CRITERIA IN THE TIME DOMAIN

In previous research [8] the IAE (Fig. 6) and the Integral of squared time multiplied by squared error (ISTSE) (Fig. 7) were found to deliver the best results in the time domain.

Both criteria assess their rating on the basis of the step response, specifically the time behaviour of the error e(t), with e(t) being the absolute difference between the reference value w(t) and the actual value x(t) (1). While IAE integrates the absolute area of e(t) (2), the ISTSE (3) imposes a considerably higher focus on the error, the further back in time it arises. Both will be minimised in the optimisation [5].

$$e(t) = w(t) - x(t) \quad (1) \qquad IAE = \int_0^t |e(t)|\,dt \quad (2) \qquad ISTSE = \int_0^t e(t)^2 \cdot t^2 dt \quad (3)$$

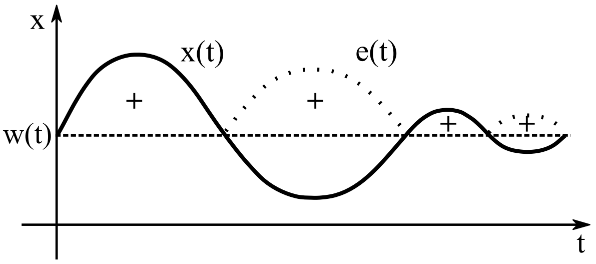

Fig. 6. Integral of absolute error (IAE) of e(t) [8]

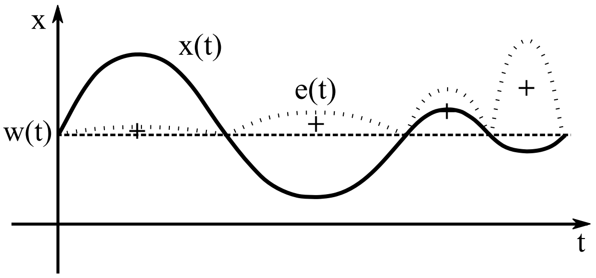

Fig. 7. Integral of squared time multiplied by squared error (ISTSE) of e(t) [8]

5.2. CRITERIA IN THE FREQUENCY DOMAIN

Preceding studies [7], [16] found the BW and the crossover frequency (CF) to be the criteria delivering the best results in the frequency domain.

The CF describes the frequency in the open loop at which the amplitude in the bode plot is 0 dB (Fig. 8), thus there is no system reaction at this point. The BW is the frequency, at which the amplitude plot crosses -3 dB in the closed loop (Fig. 9). High values of these criteria signify a higher dynamic of the control loop and will therefore be maximised, which may lead to a higher overshoot [3].

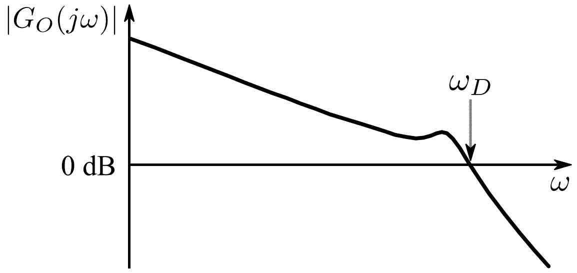

Fig. 8. Frequency criterion crossover frequency [7]

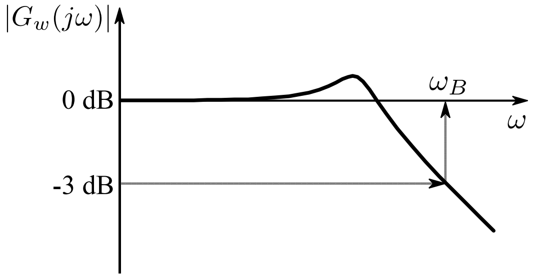

Fig. 9. Frequency criterion bandwith [7]

5.3. CONSTRAINTS

To influence the performance and stability of the system, different constraints can be enforced. In the time domain, the overshoot can be penalised if it reaches more than 20 %. In the open loop of the frequency domain, the minimum allowed phase margin at the CF, which indicates the stability of the control loop [19], is sanctioned if it undercuts either 30° or 60°.

The amplitude of the bode plot of the closed loop can be restricted by a static limit of 1.2493 dB (Corresponds to a PT_2-system with a damping of 0.5 to allow a small overshoot). [13],[17] or a dynamic limit, ascending in an exponential function from 0.37 dB

(1/e) until it reaches 1.2493 dB at the BW frequency, then declining at 20 dB per decade down to 0 dB [17], as shown in Fig. 10. The sensitivity function [12], describing the impact of disturbance inputs on the control loop, can be restricted with a static limit of 3.33 dB* or a dynamic one. This limit is equivalent to the dynamic one described above, but horizontally mirrored at the BW and reaching up to 3.33 dB.

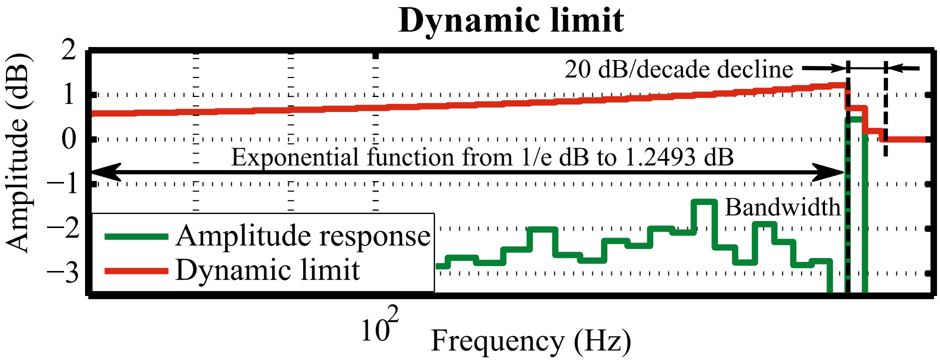

Fig. 10. Dynamic limit in the closed frequency loop control response

5.4. USED TEST METHODOLOGY

All combinations of these criteria were simulated and analysed with and without a VSF. When disabled, *T_DSWF* of the VSF was set to the simulation step time of 125 μs. Additionally the time fitness value was weighted at either:

- 100, to impose effects in the same order of magnitude between time and frequency domain,
- or at 1000 to increase the time criteria influence,

resulting in 192 different arrangements total. To make the results comparable not only through the arbitrary fitness value, each of the 192 controller settings is rated according to its IAE and its average of rise and settling time (ARST). The rise time is the time of x(t) reaching the index value for the first time. The settling time describes the duration it takes x(t) after the initial step to enter and stay within a tolerance band of ± 3 % of the reference value (Fig. 11).

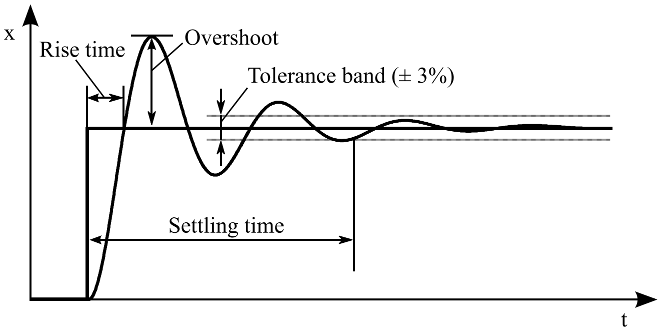

Fig. 11. Raise and settling time of a step response

6. OPTIMISATION RESULTS AND EVALUATION

To evaluate the optimisation results, all runs with identical constraints and time weight were ranked by their respective IAE and the ARST. Another distinction was made, whether a VSF was used or not. Hence, for every possible combination of main optimization criteria, 48 variations of constraints, weight factors and filter use were investigated.

Run 1, 3, 5 and 7 in Table 2 are the results which achieved the lowest ARST or the lowest IAE regarding all possible constraint combinations with minimal stability requirements (grey background). Run 2, 4, 6 and 8 (white background) display the best runs using the practically relevant setting of constraints, comprising:

- maximum overshoot of 20 %,
- a minimum phase margin of 30°,
- a static amplitude limit and
- a time weight of 1000,

which delivered reliably good results. Run 1 to 4 feature the best runs with enabled VSF optimisation. The runs are compared to the results of the Siemens automatic drive tuning algorithm with a resulting K_p of 1.309, a T_n of 6.85 ms and no activated VSF.

Table 2. Comparison between results of the runs with lowest IAE or ARST and the estimated Siemens setting

No.	1	2	3	4	5	6	7	8	Siemens
K_p	1.969	0.678	1.819	0.677	1.472	0.678	1.081	0.678	1.309
T_n (ms)	4.139	11.817	4.174	11.828	5.638	11.818	47.169	11.818	6.850
T_DSWF (ms)	1.402	0.125	0.483	0.125	0.125	0.125	0.125	0.125	0.125
IAE	0.131	0.237	0.139	0.238	0.133	0.237	0.274	0.237	0.142
ARST	7.875	12.813	7.562	12.813	7.438	12.813	5.937	12.813	7.440
VSF optimisation	Yes	Yes	Yes	Yes	No	No	No	No	-
time domain	IAE	IAE	IAE	IAE	IAE	IAE	ISTSE	IAE	-
frequency domain	BW	CF	CF	BW	CF	BW	BW	BW	-
time weight	1000	1000	100	1000	1000	1000	1000	1000	-

The results show that the runs 1, 3 and 5 achieve a better IAE than the Siemens setting. Run 7, however, performs over 1.5 ms faster in the ARST. Run 5 surpasses the Siemens setting in both IAE and ARST by taking advantage of a slightly higher overshoot.

The runs 1 and 7 both manage to enhance one of the values, compared to Siemens while additionally fulfilling the higher demands of the practically relevant constrains and therewith undercutting a maximum overshoot of 20 %. The Siemens setting leads to overshoots of more than 40 %, as seen in Fig. 12.

It also stands out that for these best runs that including the VSF time constant did not affect the results significantly. There is an exception with a distinct increase in the ARST from run 7 to run 3. This results in a reduced IAE of roundabout 50 %. However, in an overarching observation of all runs, including a VSF leads to an average reduction of the IAE value by 12 % at the expense increased ARST vales of roughly 2.5 %.

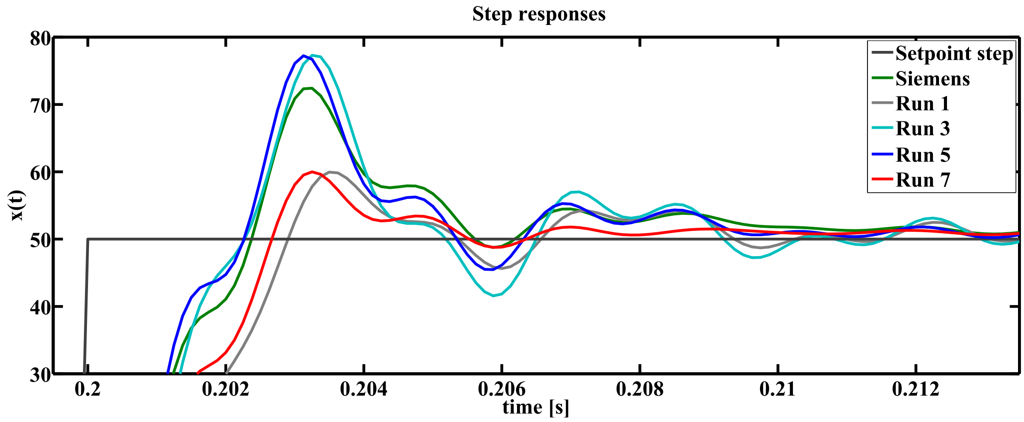

Fig. 12. Step response of the control loop for Siemens and runs 1, 3, 5 and 7

Fig. 13 presents the corresponding bode plots to the runs displayed in Fig. 12. All runs perform very similar in dynamics and stability and only run 5 is slightly deviating from the others.

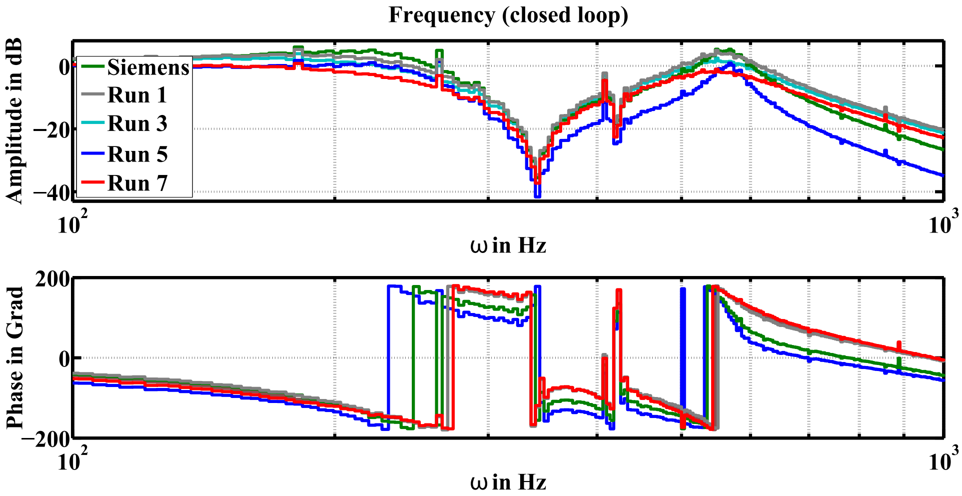

Fig. 13. Frequency response of the closed control loop for Siemens and runs 1, 3, 5 and 7

After sorting all runs by their respective constraints, time weight and the existence of the VSF optimisation, they got assigned their corresponding IAE and ARST values for each of the four time domain and frequency domain criteria combinations. Separated by these criteria, the four respective values got ranked, and assigned a score from 1 (best, lowest IAE or ARST) to 4 (worst, highest IAE or ARST).

Averaging these scores over all constraints and weightings, it resulted in a score for each criteria, evaluating the criteria quality for the corresponding benchmark criterion as shown in Table 3.

Table 3. Average ranking of criteria combinations over all 24 constraint combinations

Ranking criterion	**ARST**				**IAE**			
	VSF		no VSF		VSF		no VSF	
	BW	CF	BW	CF	BW	CF	BW	CF
IAE	1.65	1.63	2.42	2.38	1.42	1.67	1.58	1.83
ISTSE	3.29	3.44	2.15	3.06	3.29	3.63	3.08	3.50

In the frequency domain the BW criterion performs slightly better than the CF. This becomes especially apparent when combined with ISTSE. In combination with IAE the chosen frequency criterion barely impacts the score when competing in ARST. It stands out that the IAE criterion performs consistently better than ISTSE. In total IAE achieves an average rating of 1.82, clearly leading to better results than ISTSE with 3.18 (Table 4).

For an unknown system, the combined utilisation of IAE and BW are advisable, which stands in accordance with former research, recommending them separately [7], [8]. Furthermore, it is advised to use a weighting factor of 1:1000 (frequency: time), which delivered consistently better results than 1:100.

Table 4. Global average ranking of optimisation criteria

	BW	CF	**average**
IAE	1.77	1.88	**1.82**
ISTSE	2.95	3.41	**3.18**
average	**2.36**	**2.64**	

An important observation in the process was the elevated strain on the optimiser by adding the VSF time constant and therewith increasing the optimisation problem to a dimension of 3. Since fewer particles find the best solution in the increased search space, there is a higher variety in their results, therefore resulting in a higher uncertainty in the outcome.

To proof the correctness of the simulation model as well as the optimisation results, the found best runs were verified on the presented test rig (Fig. 3). In Fig. 14 , three different settings are shown. In the left figure, the step responses from the test rig and the simulation model for the auto tuning setting of the controller (K_p = 1.309, T_n = 6,85 ms, VSF turned off) are compared. It is clearly evident that they are corresponding very closely, leading to the conclusion that the model is suitable for controller optimisation. Furthermore, the representation of the optimised settings 5 and 3 (middle and right) is likewise adequate, which proves the applicability of the SBO for electromechanical axes. The given constraints in the optimisation are also satisfied in reality (in the step responses as well as in the bode plots). Hence the flexibility of the SBO can be used for tuning axis controllers in various use cases.

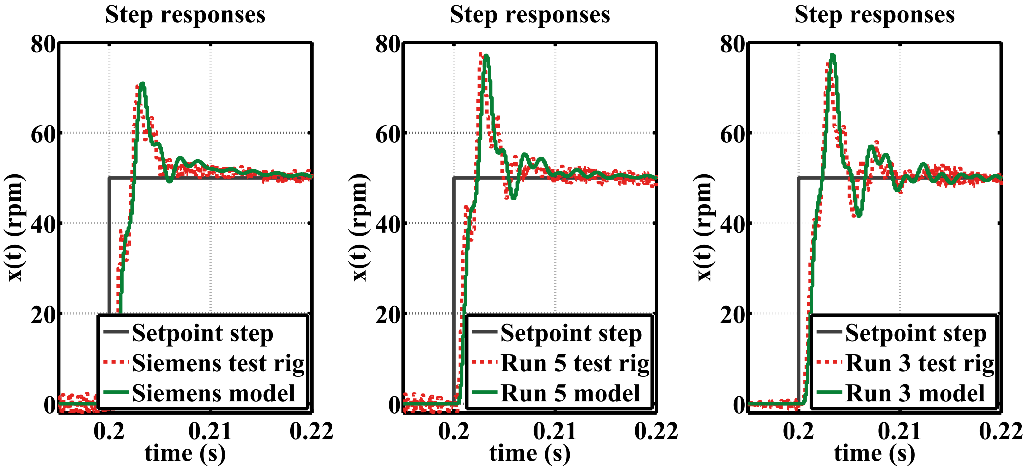

Fig. 14. Comparison of different settings between the simulation model and the test rig

7. CONCLUSION

SBO is a promising approach to parameterise controller cascades in standard industrial controllers. The quality of the achievable results is significantly dependent on the choice of optimisation criteria. Prior studies proved that IAE and ISTSE in the time domain and BW and CF in the frequency domain deliver reliable results.

In this paper a combination of both optimisation criteria and constraints from time as well as frequency domain were investigated for their feasibility as SBO criteria. The results show that especially a combination of IAE and BW provides valuable results with a weighting factor of 1:1000 (frequency: time). Furthermore, the addition of a VSF, immensely reduces the average IAE, while increasing the optimisation dimension and slightly slowing down the ARST. To proof the correctness of the used model and the optimisation results, various settings were tested on the test rig. It could be demonstrated, that the results of the optimisation are correct and the course of action is suitable.

Subsequently, in recent research the application of the proposed method was also tested on different and more complex structures. For example the controller parameterisation of the test rig was extended to include up to four current setpoint filters in the optimisation. Beyond, by adding another mass to the test rig, the results for a three-mass system were also examined. The application on a machine tool like a servo press is actual under investigation.

It could be summarized that, in comparison to other methods, the application of the SBO allows to parameterise even complex controller structures in combination with non-linear models of the investigated systems. The velocity cascade, including current control, could be parameterised in one step, too. The extension to the complete position cascade is also feasible. The possibility of nearly freely defining different constraints to affect the solution in the desired way is another significant advantage.

Still, future research can for instance supply improved insights on the specific impact of individual constraints.

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