Review of Martin Goubej's doctoral thesis

entitled "Robust motion control of flexible electromechanical systems"

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1 Description of the work

In his doctoral thesis Martin Goubej investigated several motion control design issues relevant for mechanical systems exhibiting weakly damped dynamics. Namely, he claims contribution to these three (sub)domains: 1.) automatic experimental system identification of flexible mechanical systems, 2.) input shaping for flexible mechanical systems, and 3.) feedback control of flexible mechanical systems.

Automatic identification of oscillatory electromechanical systems

In the first domain, the task is to identify one (or several) mechanical resonant frequencies accurately. The accuracy of the identified resonant peaks deteriorates in presence of nonlinearities such as friction or backlash; these distort the frequency content of the measured data by contributing to the first and higher order harmonics. The candidate's idea is to design an automated experiment which avoids exciting the nonlinear part of the dynamics, hence makes the identification of the linear part of the dynamics more accurate. The candidate proposes a special parameterized *test signal* (sweep signal with monotonically increasing frequency and tunable amplitude and DC offset). While the experiment is running, at a given frequency the two other parameters are automatically readjusted so that the higher-order harmonics are suppressed in the measured data, that is, the nonlinearities such as friction or backlash are not detectable in the measured data. This real-time detection is realized by means of a higher-order observer.

Passive vibration damping using input shaping method

In the second domain, the candidate starts with a plant containing a single resonant mode. He fixes the structure of the input shaper to four pulses. Applying the condition that the transfer function of the input shaper should vanish at the resonant frequency of the plant, four degrees of freedom are left to tune the shaper. The candidate then (somewhat arbitrarily) imposes a restriction that distances between subsequent pulses are identical. This restricts the number of degrees of freedom to two. He then proposes a new coordinate transformation which makes the set of admissible values of the two "tuning" parameters nicely regular (rectangular). He offers an intuitive interpretation of the two new parameters and demonstrates that with this new parameterization all the existing cases such as ZV, ZVD, ZVDD and some more can be recovered. Discrete time implementation is discussed and extension to systems with multiple resonant frequencies is sketched.

Active vibration control

In the third domain, the candidate considers the classical task of design of a feedback controller for a mechanical system consisting of a rigid body and a weakly damped (resonant) mode. He mainly focuses on design of simple and practical controllers of PI and PID types. Noting that the interconnection of a PI (or PID) controller yields a fourth-order closed-loop characteristic polynomial, the candidate analyzes very carefully the inherent constraints on the achievable performance by studying the rules for this closed-loop characteristic polynomial root locus. Having just two tunable parameters, he fixes the damping ζ^* of one of the closed-loop pair (corresponding to $s^2 + 2\zeta^*\omega^*s + (\omega^*)^2$) and while varying its natural frequency ω^*, he studies how the root locus of the other pole pair evolves. Furthermore, he conducts this analysis for several values of the resonance ratio $r = \frac{\omega_z}{\omega_n}$ of the plant. This way he analyzes the inherent constraints in achievable performance, namely, the achievable closed-loop bandwidth and damping. He also extends the analysis so that it includes a linear damping (friction) in the system and multiple resonant frequencies.

Then, after having the tools for analysis at hand, he proposes a control design procedure. Here I am a bit less confident I understand the essence of the method. This is how I understand it: Since it is known that for a low resonant frequency ratio r the system is difficult to control, the first (optional) step consists in increasing r by introducing a derivative feedback. The system with a derivative feedback loop is then better prepared for a subsequent design of a PI controller. Such design then consists in following the guidelines developed in the first part of the chapter—the choice of the natural frequency of one of the two pole pairs must be done such that the closed-loop bandwidth is maximized and the resonant peaks are minimized. This "optimization" is done manually in an iterative way.

In the later part of the chapter the candidate also discusses two more control design methodologies—LQG- and $\mathcal{H}_\infty$-optimal control designs and offers some guidelines for using these efficiently for mechanical systems with resonances.

2 Major comments on the thesis

Taking into consideration that the candidate is now accomplishing the last and the highest stage of higher education, I must conclude that the sheer volume of knowledge that he mastered (as reflected through the thesis) is awesome and its width is far beyond what a common graduate in control engineering can demonstrate: experimental identification of dynamical systems, classical control design (PID, frequency methods), modern (optimal) control design (LQ, Hinf), input shaping, flexible structures control, numerical optimization, electrical motors and drives, sensors, real-time implementation of the controller code, . . . I appreciate this learner's achievement very much.

I find it a lot less favorable that the candidate decided to display all these learning achievements in the thesis—the thesis is more than three hundred pages long! A major reason for this is that the first hundred pages is dedicated to the "Preliminaries" (Chapter 2) and "State of the art" (Chapter 3). I cannot help but I find very little use for these pages. In fact, I can hardly distinguish between these two chapters and I would rename them both to "What is known from standard textbooks". I am positive that there is no point in introducing in the doctoral thesis the concepts such as least-squares optimization, pseudo-random binary signal, Hooke's law, ARMAX model, Euler-Lagrange equation, sensitivity function and many more. These are all very well established concepts that have found their way to standard control engineering curriculum. And even if not, nowadays they are within one or two mouse clicks away (say, in Wikipedia). Moreover, as I document below, the treatment of these fundamentals in the thesis is (inevitably) too superficial and sometimes even inaccurate. If instead true overview of ten or twenty most important recent (say, published after 2005) journal papers for each of the three domains are carefully analyzed, the benefit will be much larger. This is what I understand under "State of the art".

Finally, the outcome of the doctoral studies— the thesis—is going to be scrutinized for a concrete original research contribution to the discipline. I have documented my own understanding of the (claimed) contributions in the previous section and below I am giving my evaluation of the candidate's contribution(s).

Automatic identification of oscillatory electromechanical systems

The individual ingredients of the proposed automatic identification procedure are fairly standard. What is innovative is their combination. Although it seems purely heuristic, its functionality has been demonstrated using simulations and experiments. I believe that there is a good chance to have this result accepted in the form of a paper to some application-oriented journal such as *Mechatronics* (journal of IFAC, published by Elsevier). Note however, that the frequency-domain approach to modeling of nonlinear systems has already been explored a lot. Among the more recent achievement, the researchers from TU Eindhoven have coined the term *Higher Order Sinusoidal Input Describing Function (HOSIDF)* which makes examination of higher order harmonics systematic, see [7] and [9]. Rest assured that the research interests of this particular group around prof. Maarten Steinbuch are perfectly driven by realistic and practical industrial problems. Unlike the submitted thesis, the HOSIDF approach is not motivated to discard the nonlinearity from the model but rather to include it, hence it prepares the grounds for frequency domain control design techniques for systems with friction and backlash.

Passive vibration damping using input shaping method

I regard the presented investigation in the domain of input shaping techniques truly interesting. I only find it a bit disconcerting that the *equidistant-pulse* restriction imposed on the four-pulse input shaper was introduces without any discussion of its impact. How much are we losing by imposing it? Why not assuming, say, that three out of four pulses have equal amplitudes instead? Anyway, the coordinate transformation from the remaining two free "physical" parameters to the two new "still-intuitive" parameters, which reshapes the feasible set into a nicely regular (rectangular) set, is clever and as far as I know it is new and original. Its value is that now the design of input shapers can be cast as a convex optimization problem with a straightforward possibility to realize a trade-off between the robustness and attenuation of residual oscillations. If only this optimization-based opportunity was developed in some more detail, ideally with the *modeling uncertainty* characterized by the automated experimental identification procedure (described in the previous chapter). I think that the complete procedure would be certainly worth submitting to some first-class control theory journal. It is a pity that the candidate has not done it yet. The feedback from the major contributors to this topic would certainly have helped improve the result (and the thesis).

Finally, the last section (a shaper in the open vs. closed loop) of this chapter was a perfect opportunity to compare the proposed results with the state of the art. In particular, instead of spending the candidate's (and the reviewer's) time on the first hundred pages filled with the textbook material, here I would love to see a detailed comparison with the cited *inverse zero vibration shaper* [11] developed by our colleagues Tomáš Vyhlídal, Vladimír Kučera and Martin Hromčík (hence easy feedback and further interaction with them). It is a pity the advantage was not taken. Mere mentioning that in this and that paper they investigate similar things is not enough, I am afraid.

Active vibration control

The analysis of the pole placement problem using a PI or PID controller plugged in a feedback loop with a third-order linear system containing a pair of resonant poles (later extended into just weakly damped poles) and one integrator (later extended to a first order system) and a pair of complex zeros is very careful and detailed. It provides some new (at least for me) findings about the inherent limits on achievable closed-loop performance, which can then be used as guidelines for tuning the controller's parameters.

Even though I would be very much surprised if in the last sixty years nobody has investigate the same fundamental issue of limits of achievable performance while using a PID controller for a flexible mechanical system, the fact is I cannot find any systematic treatment of this topic in the available literature. However, once again, it is only through submitting to a first-class journal such as IFAC Automatica or IEEE Transactions on Automatic Control that we can all make sure if the proposed methodology is truly new. In order to succeed, I am sure it is crucial to show how the proposed results on inherent limits of achievable performance (bandwidth, resonant peak) relate to the many available results for the same type of analysis (nicely summarized in the chapters 5 and 6 in [10]).

I am missing, though, some culmination of the analysis procedure proposed in this chapter into some optimization-based automatic design procedure. The optimization goals are: maximize the bandwidth while keeping the peaks of the amplitude frequency response below some limits. The understanding of coupling between the controller parameters and this optimization criterion is investigated in the first part of the chapter. Why not combining these two into a single automated procedure?

Or, it may be the case that I have just missed something important in this section. Honestly, I find the explanation here quite difficult to follow. Perhaps better structuring of the text into subsections, theorems, remarks, examples could help.

In this chapter, robustness aspects are also introduced into the procedur by using the interval model of parametric uncertainty. However, this model is not the tightest one for modeling the uncertain physical parameters and it gives very conservative results. I see no discussion of this issue in the thesis. On the other hand, I find no discussion of exploiting the model of the system obtained by the experimental methods developed in Chapter 5, including the information about the uncertainty (perhaps some variance estimate).

The discussion of the usage of two more well-established control design methodologies—LQG- and $\mathcal{H}_\infty$-optimal control designs—for flexible mechanical systems is significantly "lighter" and essentially offers a contribution to the bag of heuristic (albeit practically useful) engineering *rules of thumb* rather than a rigorous analysis. For example, neither theoretical not numerical issues with poles and zeros on (or close to) the imaginary axis for $\mathcal{H}_\infty$-optimal control are mentioned.

Finally, how about combining the feedback design with the input shaping in one computational procedure? That is, not designing the two separately/independently but solving both design tasks at once? The methods for design of structured controller design are now available (`hinfstruct()` in Robust Control Toolbox or `hifoo()` downloadable from `http://www.cs.nyu.edu/overton/software/hifoo/`)?

Overall evaluation / recommendation

To summarize, the thesis contains some original real-life motivated research results. These are reasonably well described and experimentally verified, which makes them perfectly relevant for automation industry, especially the motion control area. On the other hand, although the thesis contains a wealth of references, I am missing a bit more detailed analysis of the shortcomings of the existing techniques and then their comparison with the proposed solutions. It is also a pity that the work was not exposed to tough but highly-qualified international scrutiny by submitting its part(s) to a first-class journal such as Automatica, Control Engineering Practice, IEEE TAC or TCST. **I recommend the thesis for the defense.**

3 Minor technical issues, comments on notation, terminology and typos

The minor issues listed here shouldn't certainly be discussed during the official defense but are given with the good will to help improve the manuscript just in case the candidate wants to publish a part (or parts) of it later as a regular journal paper(s).

Chapter 2—Preliminary chapter

1. The left and right brackets in (2.1) and elsewhere in the work should be typed such that they correspond in size to the enclosed content. This can be easily achieved with `\left(` and `\right)` commands in Latex. The equation (2.1) would then look like

$$\|z\|_p = \left(\int_{-\infty}^{\infty} |z(t)|^p \mathrm{d}t\right)^{1/p}.$$

2. Still referring to the same equation (2.1), I recommend considering using the upright font for differential d in integrals. This is certainly not kept by every author but I find it a useful habit in order to emphasize that the role of d is different from other symbols which stand for variables such as t typeset in italics.

3. Still continuing this upright vs. italics case, I find it very useful to typeset some other keywords within formulas such as sup in (2.3) in the upright case (there is even a command for this in Latex—`\sup`). The reason is that sometimes this may help avoid inappropriate interpretation as s times u times p. Similarly tr in (2.10).

4. After having introduced the $\mathcal{L}_2$ signal norm in time domain, in (2.5) you say that it can also be defined "analogously" in frequency domain. I find this statement rather confusing. Although you emphasize that the object of interest—$z(s)$—is not a Laplace-transformed signal, I think that this should better be also reflected in the notation. Something like $z(t)$ for the time-domain signal and

$\hat{z}(s)$ for its Laplace transform. True, many authors are freely committing this notational abuse too but the reader should be at least warned that $z(t)$ and $z(s)$ are two very different objects. Reading on, I find it rather inconsistent that on some occasions the distinction is made in this work (for instance in (2.7) and (2.8) when the impulse response is labeled $h(t)$ and the transfer function is $H(s)$), which is perfectly correct, and then on the next page in (2.11) gives the apparently frequency-based two-norm of y while the input is U.

5. Note that the definition of the 2-norm of a frequency-domain signal in (2.5) that features the $z(-s)$ term is not valid generally. For rational $z(s)$ it is only valid if all the coefficients of the numerator and denominator are real since only then it can replace $\bar{z}(s)$ on the imaginary axis.

6. On page 7 you write that "The notation H_2 which is often used instead of L_2 is a reference to Hardy spaces of bounded and analytic functions in the right-half plane". This is rather confusing if you do not specify the support of the $\mathcal{L}_2$ functions first. Does it denote the time-domain signal supported on $t \in (-\infty, \infty)$? Or $t \in [0, \infty)$ or even $t \in (-\infty, 0)$? Or frequency domain signals with the support on $s \in (-\infty, \infty)$? This is not explained in the text. In fact, $\mathcal{H}_2$ can be viewed as a subset of the "frequency-domain" $\mathcal{L}_2$, which is often labeled as $\mathcal{L}_2(j\mathrm{R})$ in order to distinguish it from the time-domain signals labeled $\mathcal{L}_2(-\infty, \infty)$, $\mathcal{L}_2[0, \infty)$ and $\mathcal{L}_2(-\infty, 0)$. The relationship between $\mathcal{H}_2$ and $\mathcal{L}_2[0, \infty)$ is then that of an image and preimage in Laplace transform. Furthermore, your sentence contains "bounded and analytic", which is also misleading. First, $\mathcal{H}_2$ is a set of functions that are analytic *and* that satisfy certain integral condition. It is only the special case of rational function for which the analyticity (the absence of poles in the closed right half plane) is enough. Such space is then referred to as $\mathcal{RH}_2$. Second, what is meant by "bounded and analytic"? See Chapter 2 in the online available [2] for a quick overview.

7. The above point was not meant to be pedantic. What stimulated it was actually the possibility of a noncausal response indicated by the lower integration bound in (2.7), in which case the impulse response is in $\mathcal{L}_2(-\infty, \infty)$ for a stable system and its Laplace transform is in $\mathcal{L}_2(j\mathrm{R})$, that is, its transfer function can have no poles on the imaginary axis but can easily have poles in the right half plane.

8. While introducing the LQG optimal control on page 9, it is stated in the sentence following (2.18) that the matrices A and C defining the state-space model must be observable. This is not correct! The standard state-feedback version of the problem (and it is apparently the version that you are studying because you ultimately obtain a state-feedback control in (2.20)) is conditioned by the stabilizability of A and B (stabilizability is enough, no need for controllability) and detectability of A and $\sqrt{Q}$! Observability might be requested instead of mere detectability if one desires avoiding a trivial "zero controller" in situations such when $Q = 0$ and the plant itself is stable. Nonetheless, beware that it is Q that enters the game here and not C! In fact, the whole LQG control design strategy does note care about C since it assumes availability of the feedback measurements anyway.

9. In displayed multiline equations such as (2.10), do not use the "=" symbol both at the end of the previous line and the beginning of the following line. This is an unnecessary duplicity. Nick Higham writes in [4] the following advice:

   > When a displayed formula is too long to fit on one line, it should be broken before the binary operation[...] A formula in the text should be broken after a relation symbol or binary operation symbol, not before.

10. I also do not find the introduction of the LQG problem complete without stating the necessary constraints on the matrices Q and R in the optimization criterion (2.19), namely that $Q \geq 0$ and $R > 0$. These are quite important.

11. On page 10 you call the matrices V and W *covariance matrices.* Although this is perfectly correct for discrete-time random processes, the true covariance (function) for a zero-mean white continuous-time noise is $E[w(t)\, w^{\mathrm{T}}(t+\tau)] = W\delta(\tau)$, where $\delta(\tau)$ is a Dirac "function".

12. There is a notational inconsistency between the sections 2.1 and 2.2 regarding the imaginary unit $\sqrt{-1}$. In the former you use j whereas in the latter you use i.

13. On page 13, the symbol "$\sim$" is left undefined. It is not clear at all what $A+BF \sim L$ means. Does it mean similarity of two matrices? But how is it then interpreted if the dimension of L is less then that of A? It should have been stated in the text in order to avoid confusion.
14. On the same page in (2.41), it is quite confusing to see the same symbols both in boldface $(\mathbf{A}, \mathbf{B}, \mathbf{F})$ and plain (A, B, F). Is there any reason for this?
15. The information on page 14 about a freely available toolbox provided by your department is not quite useful if you do not give a link where such toolbox can be downloaded.
16. Figure 2.1 is not very aesthetic because of the completely inappropriate size of fonts. Try making the fonts both in the figures and in the text of comparable size.
17. There is much more to the practically useful line search methods than what is captured by (2.69)—see dedicated sections in [6], [5] or [1]. I am not suggesting to include these practical issues here, quite the contrary, I just dispute usefulness of having this "not very short" intro to optimization when it is by the very principle overly simplified.

Chapter 3: Motion control—state of the art

1. In section 3.1.1 on sensors on page 27 you mention that magnetic sensors of angle can be used in low cost applications, which suggests their inferior performance. However, this section would better reflect the current "state of the art" if it is mentioned that nowadays even 360 deg sensors with a 12-bit resolution are available, see, for example `http://www.allegromicro.com/en/Products/Magnetic-Linear-And-Angular-Position-Sensor-ICs/Angular-Position-Sensor-ICs.aspx`.
2. When discussing the state of the art in processing the data from incremental encoders to obtain the estimate of velocity on page 27, you only mention that apart from computing the number of pulses in a given time period, there are some interpolation techniques or state observer-based estimation techniques. This is an important problem of uppermost practical importance, especially when low angular rates are required. I am convinced that there is much more to the actual state of the art in this domain than what you mention here. See the Chapter 5 in the final year undergraduate thesis by Martin Gurtner [3] and the references therein.
3. When introducing accelerometers in section 3.1.1 on page 28, you make a reference to "gyroscopes" but these were not introduced in the corresponding section on velocity sensors; not even a word about them.

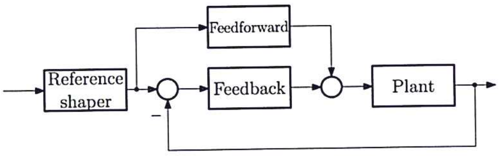
Chapter 5: Automatic identification of oscillatory electromechanical systems

1. It seems to me from the description of the observer in (5.5) on page 106 through 107 that the signals $\hat{z}_i$, $i = 1, \ldots n$ are just sines and cosines of unit amplitude. I can see no A_i, $i = 1, \ldots, n$ there such as (5.10) suggests.
2. Where is the adaptation mechanism for the DC bias (offset) $u_o(t)$ declared in (5.1) on page 104 actually described in the thesis?

Chapter 6: Passive vibration damping using input shaping method

1. In this chapter you used the term "Passive" to characterize the proposed control strategy while in the next chapter you use the term "Active" to characterize another approach. Although I am aware of the usage of these two terms in the flexible structures control community, please note that they assume different meanings (energy-related) in the rest of the control engineering community (as well as electrical circuits community), see [8]. Some warning should have been inserted. In addition, the statements like "passive approach [...] tries to minimize the amount of energy" contribute to confusion; there was no discussion of minimization of energy in the thesis.

2. I object against the usage of "feedforward controller" in place of "input shaper" (at the bottom of page 157). When a feedback loop is closed, these are not identical. My viewpoint is explained in the figure below. I agree that numerous textbooks on automatic control (theory) by well respected authors use them interchangeably, though. As a consequence of this "relaxed approach", most graduates are rather unaware of usefulness of the (true) feedforward control. Ignoring or misunderstanding this smart idea in the motion control are leads to suboptimal designs.



3. On page 187 you give several transfer functions and among them the transfer function of the input shaper F. You give it in the fractional form as $F(s) = n_f(s)/d_f(s)$ in (6.80) but then the denominator d_f is absent in the closed-loop transfer function (6.81). You should have explicitly stated that for your class of input shapers, there are no poles, hence no denominator. Otherwise it is confusing.

Chapter 7: Active vibration control

1. I find it a little bit unfortunate that the fundamental limitations are studied for the normalized case with the numerator polynomial given by $(s+1)^2$ in (7.12) on page 199. The reason is that in the subsequent analysis it is not clear how the zeros are projected into the constraints. Or I just do not feel comfortable with the fraction of the two frequencies ω_z and ω_n that you call r.
2. What is the meaning of the $\wedge$ sym bol in (7.90) on page 217? It is undefined. Similarly in (7.111).
3. Most figures with three plots are very limited in usefulness since one can hardly read the axis labels and legends. See the Fig.7.12, for example.
4. While introducing the terminology "load side" and "motor side" in the thesis, it may be useful to mention that there is another related terminology of "collocated" and "non-collocated" frequently used in the control literature. It may help find some more related works.

Chapter 8: Application results

1. It is great to have such chapter in the thesis, but much more benefit could be delivered to the reader if instead of the screenshots of GUI's, the physical parameters for the models are given. The reason is that only if the whole control design procedure can be fully reproduced by another researcher (or student), the work can be declared verified. There seems to be an even better solution: upload the mathematical model to some public web page. Say, Matlab and Simulink files can be uploaded to *Matlab Central* such as: `http://www.mathworks.com/matlabcentral/fileexchange/42845-structured-mimo-h-infinity-design-for-a-dual-stage-platform-using-hifoo-and-hinfstruct`. I think this should become standard in reproducible research. See the discussion at `http://goo.gl/gC5zsu`.
2. In the screenshot in Fig.8.3 and possibly elsewhere in the thesis, you use the term *engine*. Although I am not a native English speaker, I suspect that the prevailing usage of this term is for combustion engines. I doubt that, say, Maxon company produces engines. Use (electric) *motor* instead to be on the safe side.

References

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[4] Nicholas J. Higham. *Handbook of Writing for the Mathematical Sciences.* SIAM: Society for Industrial and Applied Mathematics, Philadelphia, 2 edition edition, August 1998.

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V Praze 3.4.2015

Assessment of PhD Thesis

Name of the PhD Student: Martin Goubej

Title: *Robust motion control of flexible electromechanical systems*

General remarks, introduction and objectives

The top quality PhD thesis, which is written in a monographic style, consists of nine chapters including introduction and conclusions. The thesis is written very carefully and in very good English. The overall number of pages is 304. Already this number itself is remarkable, taking into account fairly dense formatting (Times New Roman, 11pt, line spacing one). The number of references in Bibliography is 225. Next, the author provides a list of publications where he is the main author or a co-author. The list consists of 16 references to conference papers (five of them sponsored by IFAC or IEEE) and one journal publication (AT&P Journal PLUS). Four of these papers can be found in the ISI Web of Science database, with none citations so far. The database Scopus registers 11 references with five citations (H-index 2).

The thesis starts with an extensive preliminary part, which includes three chapters. After a brief **chapter one** with a general introduction and thesis outline, **chapter two** provides definitions of tools for signal analysis, LQR, modal, and robust control synthesis. It also outlines methods for data fitting and least square optimization. This part is carefully written and shows that the author is able to sort out information in an easily accessible way, which can be useful for his academic career. However, for the purpose of the PhD thesis, it is perhaps too detailed; definitions of some of the control theory and data processing basics could have been omitted.

The **third chapter** provides a state of the art to the motion control. It starts with an outline of the motion control concepts and then it provides a critical survey on sensors and actuators in this subject. A particular emphasis is laid on electrical drives. The chapter then continues with an outline of typical problems in trajectory generation and motion control. So far rather descriptive part is followed by detailed, model based studies of motion control for rigid mechanical systems, which includes i) current and torque control in electrical drives, ii) speed and position control of rigid mechanical systems describing the optimal, pole placement and robustness region methods, and iii) multivariable motion control. The key part of the chapter is then focused on analysis of flexible mechanical systems. The analysis starts with the problem definition and outline of modelling approaches for the given task. Then, the lumped parameter modelling approach is demonstrated on several typical applications, including two-mass system, which is the key case study for the thesis. The derived models are subsequently used throughout the following chapters of the thesis. Next topic being addressed is the approximation of nonlinear dynamics, such as friction and backlash phenomena. The chapter then continues with identification of flexible electro-mechanical systems. It addresses fundamental problems from data collection and model parameter fitting, to model validation. Finally, vibration control methods are outlined. First, it includes the passive vibration control methods by input shaping, which is followed by overview of the active approaches. Also this chapter is written very carefully and provides all the needed background for the main parts of the thesis. On the other hand, with its 74 pages, it is too extensive for the purpose of the PhD thesis. The author should have rather focused on the key subjects solved further in the thesis and provide critical analysis of the existing literature on these topics only. The descriptive part could have been much shorter.

Thesis aims and objectives

The **fourth chapter** then states the aims and **objectives** of the thesis. The general aim is stated as development of robust and reliable methods for automatic commissioning of velocity and position motion control loops applicable for electromechanical systems with oscillatory dynamics. The objective is to propose theoretical tools, which can be implemented in today's power electronics and real-time control systems. Three specific objectives are formulated as follows:

Objective 1 - Design of automatic identification of oscillatory mechanical systems

Specific goals:

- i) development of identification method for oscillatory mechanical systems
- ii) assessment of the linear part of the dynamics
- iii) identification algorithm adaptation with respect to the detected nonlinear mechanics
- iv) closed-loop identification scheme for unstable mechanical configurations
- v) implementation of the whole identification algorithm

Objective 2 - Design of feedforward vibration control using input-shaping method

Specific goals:

i) development of a robust and easy to tune input shaping filter
ii) discrete time implementation in a form of a functional block

Objective 3 - Design and analysis of active vibration control of multi-mass systems

Specific goals:

i) performance analysis of conventional cascade PID control structure
ii) design of automatic procedure for PID gain tuning
iii) performance analysis of higher order controllers
iv) feature based parameterization of proposed closed loop schemes

The objectives are clearly stated and it is no doubt that the solution of the highlighted problems will provide significant contribution to the applied theory of wide range of motion control problems. In this part however, one would expect more detailed justification of the objectives with respect to the existing literature.

Solution of the first objective

The first objective is solved in **chapter five.** First, the 'swept sine' signal is proposed as the system excitation signal, which is generated by proposed second order generator. The core of the identification procedure presented in the thesis is the eleventh order state observer, which works as a linear time varying system adapting its dynamics to keep synchronization with the observed system at the given fundamental frequency. Next to identifying the frequency response point (amplitude and phase) for the given frequency, the characteristics of four higher frequencies are identified, if the system is nonlinear. In order to tune the observer feedback, two approaches are proposed. First, the Butterworth spectrum pattern is considered and it is demonstrated that it can perform well if tuned properly. A drawback of this setting is a strong amplification of the signals when setting with increased bandwidth is used. This insufficiency is removed by considering the feedback design of Kalman-Bucy filter, which however requires solution of an algebraic Riccati equation and stating several simplifying assumptions, e.g. preselection of covariance matrices. Further on, it is shown that when the feedback gain is obtained for a single frequency, it can be directly recalculated to any frequency just by dimensional treatment. The subsequent part of the chapter proves that when the sweeping of the frequency is sufficiently slow, the observer is able to match the system dynamics so fast that the frequency point parameters can be assessed online during the sweep. Later on, it is shown that the sweep algorithm may be inaccurate close to the resonant and anti-resonant frequencies. The solution of this problem can be solved by stopping the frequency sweeping at preselected frequency values. Next task solved in the chapter is adaptation of the excitation signal amplitude, which takes place whenever the proposed logics of the identification algorithms finds out that the behaviour of the system is too nonlinear (due to friction, backlash, etc) or when the noise plays a substantial role. For identifying these cases, two quantities are introduced – *total harmonic distortion index* and *signal to noise ratio*. These quantities smartly utilise the characteristics of the higher frequency harmonics estimated by the observer. Another topic addressed at the chapter is parameter identification of unstable systems within closed loops. After highlighting key problems with identifying system when it is stabilised by a well-tuned controller, which in fact prevents from the excitation on its eigenfrequencies, a viable solution for the given task, a semi-closed loop scheme is proposed. The practically focused part of the chapter starts with discrete-time implementation. After providing the signal generator in the discrete form, the Tustin transform is selected for observer discretization. First, it is demonstrated that, if the pre-warp frequency is chosen identically with the fundamental frequency of the generator, the correct estimate of the frequency response point is achieved. Subsequently, the stability of the discrete observer is stated and proven in Theorems 5.6.1 and 5.6.2. The final identification algorithm has then been implemented as RFID block within both the REX control system and Matlab-Simulink (as C-MEX S-function). Finally, the performance of the algorithm is demonstrated in a simulation example. It is shown that the sweep mode, i.e. when the frequency is slowly being increased, can be supplemented by measurement mode. In this mode, the sweeping of the frequency is stopped and the single frequency point is measured with increased accuracy. Next, the adaptation of the amplitude is demonstrated.

As it results from the chapter outline, **all the specific goals of the Objective 1 have been fulfilled**. The presented identification approach is theoretically advanced on the one hand and well practically applicable to a wide range of mechanical systems on the other hand. Uniqueness of the results is in their compactness, when the theory is driven to provide safe and reliable identification algorithm that can be straightforwardly applied.

Solution of the second objective

The **chapter six** provides solution of the objective two. It focuses on the feed-forward pre-compensation of the system oscillatory modes by input shaping. After highlighting advantages of 'passive' approaches to vibration damping and providing an outline of properties of input shapers, the key contributions in this subject are presented. The first contribution extends the results presented in the author's publications [87, 206], which is the design and analysis of generalized 'ZV4' input shaper. The ZV4 is designed as a general four-impulse time delay input shaper. The synthesis is undertaken in the vector diagram from which the construction conditions on the shaper structure are derived from feasibility of a geometrical tetragon needed to achieve zero vibrations for the nominal frequency of vibrations. By parameter transformation, an elegant and easy to tune shaper parameterization is achieved. By adjusting three optional parameters, shaper insensitivity to the mismatch between the design and true characteristics of the vibration mode, can be tuned. Besides, almost all the known shaper types can be represented as sub-types of ZV4. A key benefit of the proposed approach is that unlike most of the robust shaper design techniques, it is fully analytical. These results are truly unique - no such generalization of robust shaper design can be found in literature. **I strongly recommend submitting this material to an international journal**. A subsequent topic deals with discretization of input shapers. As the main contribution, an exact discretization algorithm is proposed. The algorithm is based on vector decomposition. Each of the impulse vector is decomposed into two vectors with an angle being integer multiple of the sampling period angle. This method is elegant and performs well the given task. The second key contribution in input shaping is a design of multimode shapers using optimization technique. The procedure is based on the well-known fact [R1, R2] that when the time delays of the impulses are fixed, the shaper design is linear with respect to the remaining parameters concerning the zero-vibration requirement. Taking into account additional requirements on the shaper properties, mainly the monotonicity of the step response and unitary gain, the shaper design problem can be handled as feasibility problem of linear programming method, as already proposed in [R2], see also [R3, R4]. The main contribution in this subject is including the robustness issue by proposing the conditions on limiting the level of residual sensitivity function on the given interval close to the nominal frequency. The extension to multimode case is straightforward, as only dimension of the problem is increased. Similarly to [R2] the function to be minimized is constructed rather artificially. Even though this sub-part of the thesis provides compact design technique, in my opinion, the topic would deserve deeper analysis, and more extensive comparison with existing literature on the topic. Finally, the application of input shapers within the closed loop architectures is analyzed. However, the novelty provided with respect to existing literature is relatively mild. In my opinion, the loops addressed in Fig. 6.14 where the flexible output is measured are not relevant as they can be solved by classical closed loop techniques, which are deeply addressed in the subsequent chapter 7. On the other hand, from the input shaping point of view, the schemes in Fig. 6.15 are relevant. However, the results outlined in this part of the thesis are well known [R5, R6, 209]. Besides, the inverse shaper inclusion [209], already considered by Smith in his famous book in connection with the compensator [R6], cannot be considered just as a type of a peak filter, as it is claimed in the thesis. It is the same as claiming that the input shaping is not needed because the problem can be handled by classical notch filter techniques, which is not true.

To sum up, the chapter provides excellent results of impact journal level on the one hand, particularly the ZV4 shaper design and analysis, and inclusion of robustness aspects to optimization based design. On the other hand, the comparison of some of the results with existing literature is rather mild. It however needs to be stressed that the positive aspects and contributions of the chapter considerable outweigh those being slightly criticized. In my opinion, this topic alone could be fully sufficient for the thesis, if treated in more detail. Also here I can confirm that **all the specific goals of the Objective two have been fulfilled.**

Solution of the third objective

The last technical **chapter seven** focuses on methods of active vibration control of oscillatory electromechanical systems, with two-mass model as the case study example – considering significant elastic coupling between the actuator and the elastic driven payload. After motivating the problem under consideration, PI and subsequently PID control of single resonance system is addressed. First, fundamental limitations on the applicability of PI velocity controller are revealed, particularly with respect to the ratio between the resonance and anti-resonance frequencies. Subsequently, it is shown that the ratio can virtually be shifted by adding derivative action. Even though substantial improvement can be achieved in comparison with PI controller, still, the applicability and performance of velocity PID control have some limits, e.g. the maximum attainable bandwidth is limited by the value of the first anti-resonance frequency of the system. This first part of the chapter includes thorough analysis of the problem, using partial pole placement techniques, stability and robustness analysis, and controller performance optimization. Next to the velocity feedback, overall control scheme with position control is analyzed too. As one of the main outcomes of the analysis, a procedure for tuning the PID control loop is proposed, which can be fully automated and implemented in the drive commissioning software. In the second part of the chapter, full-order compensator design is addressed. First, by considering a general compensator for the considered case of coupled flexible subsystems, it is shown that the fundamental limitations recognized for the PI(D) case cannot be overcome by any linear controller. Subsequently, LQG control and H infinity methods are applied to quantify the possible improvement with respect to PID control scheme. From the subsequent cross-comparison of all the considered control schemes, it is shown that the modern methods bring some benefits only for systems with larger values of ratio between the resonance and anti-resonance frequencies. Otherwise, the insufficiency of the control for small values of this ratio and the efficiency in the ideal region of the ratio values are equivalent to PID control. This analysis is followed by a brief discussion of extension of the results towards multiple resonance systems. Subsequently, it is demonstrated that substantial improvement of control performance can be achieved by considering feedback from the load position (velocity). Final extension of the results deals with considering the frame flexibility in the control design. It is shown that the derived methodology can be applied also to this higher mode system.

To sum up, the chapter provides compact analysis of control problem of oscillatory electromechanical system - **all the specific goals of the Objective three have been fulfilled**. Most of the results are derived for the two mass model derived in chapter three. Even though the problem under consideration seems straightforward, interesting observations have been made concerning the resonance characteristics of the system, which next to the control can be utilized in mechanical design of the system.

Additional, application oriented results

Next to theoretical and core chapters five, six and seven, practically oriented **chapter eight** is included, which demonstrates achieved results on the problems solved in R&D research projects with involvement of the author. All the applications are briefly described and solutions of particular problems are outlined including comments on SW/HW implementation and demonstration of achieved results. For most of the applications, references to papers with detailed description of the results are included. First the application of ZV4 shaper is successfully demonstrated on a classical input shaping task of pre-compensating the oscillations of a payload at a ***crane model***. The second application is a ***rope drum control system***, which is based on combination of a gain-scheduled PID compensator with a reference set-point shaping filter. The system has been designed with ZAT a.s. company and resulted in a patent. The third example is an application of ZV4 shaper to vibration suppression in force pulsation experiments in **robotic manipulator for testing of shifting system**, which has been designed within R&D research performed in collaboration with ZF Engineering Company. Then, the application of ZV4 shaper is applied to suppress oscillations of frame oscillations of two-wheeled self-balancing robotic platform developed for educational purposes. In the fifth example, the velocity PI controller was designed to actively suppress vibrations of the platform of ***AGEBOD robot***, which was developed in collaboration with EuroTec JKR Company. Also in this application, the control system is supplemented with ZV4 to shape reference trajectories. The last and the key example is application of thesis results on a ***dynamic test bed*** developed jointly with VÚTS a.s. company for testing vibration control methods. First, the proposed frequency identification algorithm is applied to obtain frequency response of the system and consequently to parameterize the considered system model. As the resonance ratio is of convenient value, consequently, it is shown that PI controller is fully sufficient for active vibration suppression at the system. The alternative LQG a H infinity controllers can achieve comparable bandwidth as the PI. Then, a second experiment is described with inconveniently high resonance ratio excluding the efficient application of PI controller. Applicability and suitability of LQG a H infinity controllers is demonstrated by both simulation and experimental tests. To sum up, this part of thesis validates applicability and reveals high potential of theoretically proposed methods to handle challenging practical problems in vibration suppression of electromechanical systems.

Summary of the achieved results

The last chapter **nine** then provides discussion and final conclusions. As the main theoretical results, the author highlights:

1. Development of novel identification methods
2. Feature-based parameterization of single-mode zero vibration input shaping filters
3. General algorithm for multiple mode shaper design
4. Analysis of fundamental limitations on achievable quality of feedback vibration control
5. Analytical derivation of set of stabilizing PID controllers for active feedback control of oscillatory systems
6. Full order compensator design method based on LQG and H infinity framework

Next, a set of practical implications of the research is formulated and open problems are highlighted.

Overall evaluation and recommendation

The thesis presents original top quality research results from the area of identification, control design, stability and performance analysis of flexible electromechanical systems. On the one hand, solving all these issues in a single thesis allowed the author to provide general and complex procedures for handling a wide range of challenging problems in the subject of control of flexible electromechanical systems. On the other hand, this resulted in an unusually extensive thesis - the number of pages is at least twice as large as generally recommended limit 150 pages. However, the author managed to address and present all these issues in a compact and theoretically advanced way. There are only very few typographical and other types of formal errors (e.g. duplicate reference [56] and [179], [53] and [173], ... may alose be ... p. 119). Only the representation of some of the graphical results could have been better. Many of the figures are too small with almost unreadable axes and their labels. Description of some figures could have been more detailed in their captions as well as in the text. Besides, even though the number of references (225) listed in the thesis is remarkably high, the key contributions achieved in the thesis could have been more comprehensively cross-compared with the existing literature. In any case, the originality of the key results derived in the thesis is clear. In all the three key subjects being solved, at least some of the results are of impact journal quality. Particularly, these are i) the overall identification procedure proposed in the chapter five, ii) the generalization of four pulse input shaper design in chapter six and iii) the resonance based evaluation of practical controllability of flexible electromechanical systems. Hopefully, these topics will be published soon in a top quality journal in order to increase the impact of these remarkable results. An additional unique aspect of the thesis is transferring the strong theoretical results to control system software and their subsequent validation in a wide range of practical (mainly industrial) control problems handled in R&D project of applied research.

To sum up, all the three proposed challenging objectives of the thesis have been fulfilled at a high level. Therefore, it is my pleasure to recommend the thesis for defence.

Questions and comments to be addressed at the thesis defence

1) In the identification algorithm proposed in the chapter five, next to the sweeping mode, a measurement phase with fixed excitation frequency is defined on p. 125. This is a bit confusing as the sweeping signal is introduced in the beginning of the chapter as the nominal excitation signal. As demonstrated in simulation example starting on p. 153, the sweep mode can generally be used for identification of the frequency response points except vicinities of the frequency resonance points. Please, provide generalised comments on this issue.
2) When the adaptation part of the proposed identification algorithm detects nonlinearities through appearance of higher frequencies in the output harmonic signal, the amplitude of the input signal is being increased. This however can be contra-productive as the linearity is generally bounded to the close vicinity of the operational point of the nonlinear system as a rule. Please, comment on this.
3) The ZV4 shaper has been presented in publications [87, 206]. As the presented results are important contribution to the general theory of input shapers, explain why these results have not been presented in an international journal with higher impact. Are there any plans to do so?
4) Explain in more detail the claimed connection of the inverse shaper [209, R6] and the peak filter. The key idea behind using the inverse shaper in the feedback loop is to project its signal shaping characteristics to the overall closed loop dynamics. This cannot be done in analogous way by a finite order filter.
5) As the objective function to be minimised in the linear programming design of multimode shapers is defined rather artificially, the defined linear programming problem is more feasibility than optimization problem (the algorithm is searching for a setting satisfying the given constraints). A reasonable alternative would be to minimize directly the sensitivity function at the given region(s) of interest. This could be done by solving linearly constrained least-squares problem.
6) In the active vibration control of electromechanical systems, the ratio between resonance and anti-resonance frequencies is identified as the key characteristics determining the potential of PID or more complex controllers to handle the control task. In the analysis, torques at the connecting shaft are considered as system disturbances. Was the effect of different types of disturbances, e.g. acting at the sensors, considered in the performed research? Could application of input shapers within the closed loop help to handle the control task, considering even the inverse shapers in the loop? Or is the input shaping entirely ineffective for the given task due to considerable coupling effect?

In Prague, April 28, 2014

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