

## AUTOGENETIC DESIGN AND OPTIMIZATION USING REDUCED SYSTEM MODELS

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### ABSTRACT

Mechatronic systems are multidisciplinary products and therefore the knowledge required for developing such products/systems is extensive. For the optimization of a mechatronic system, it is necessary to build an overall system model. One important approach is to use reduced models that may be derived from more detailed models. The determination of some important design parameters is very helpful for using a Natural Optimisation Algorithm (NOA).

The approach of optimization using reduced system models is presented by analyzing a drive train of a rolling mill.

**Index Terms** – System models, model reduction, autogenetic design theory, optimization

### 1. INTRODUCTION

Mechatronic product development can be seen as a marriage between the several disciplines of engineering, business and industrial design. It is the ability to effectively combine and manage these areas that determines our ability to design for industry [1].

In this research work the authors reflect an approach for mechatronic system design using hierarchical models.

One of the decisive tasks in innovation processes for technical products, such as mechatronic systems, is the technical product development. Within this task, the conceptual design phase has the strongest impact on the product's success, because the main properties and costs are defined here. In this phase not many tools and methods are established to find an efficient solution for a design problem ([2], [3]).

The conceptual design phase is elemental to the process of innovation. Some performed steps are recurring in other stages, allowing the use of particular know how from conceptual design for other phases of product development and vice versa [4]. Hence, the authors see an enormous potential for a common use of methods, e.g., systems engineering. In all phases of

the design process there is a need to build models that are simplified representations of the object under consideration. In different phases these models have different aims [5]. In the conceptual phase, physical principles, functions, structures, etc. have to be evaluated by building analytical and/or physical models. In most situations analytical models are less costly and less time-consuming than (partial) model prototypes; therefore there is a tendency to use more analytical models.

Many of the analytical models can be implemented, simulated and evaluated with the help of computers.

In this research work the authors reflect an approach for modelling and optimizing mechatronic systems based on the use of reduced models (containing only the main parameters). For this purpose, a general description of product properties and characteristics for different views and granularities is strived. For example, this can be certain mechatronic characteristics (deflection, dynamics, transfer function, reference action of a control loop, etc.) during different development activities (design, modelling, analysis, testing, evaluation, etc.), the power demand, the complexity of manufacturing and assembling, or the complexity of operation and handling items.

### 2. BACKGROUND

#### 2.1. System Modelling

Today's mechanical engineering products (machine tools, vehicles, aircrafts, industrial plants, etc.) consist of multiple systems, aggregates, modules and components. They comprise power supply, mechanical, electrical, hydraulic and pneumatic drive systems and automation equipment including sensors, actuators and controllers; hence, they often represent very complex mechatronic systems ([6]). Crucial to the success of such a product is the behaviour of the overall system, as customer requirements and desires almost always relate to the whole system and not to subsystems, components, or even individual parts. To assess the

assess the characteristics of the system, it is appropriate to use models. For modelling and description of a mechatronic system it is necessary to decompose the system into a selection of suitable sub-domains, because they describe the boundaries of the considered mechatronic system to its system environment, enabling the flow of matter, energy and information.

Their function is distinguished from other systems and hence requires the clear definition of interfaces and areas of responsibility. Therefore it must be clarified in what way interactions with the system environment (e.g. chemical, energy, information) have to take place.

In the ideal case, the whole system is in the form of a cross-domain model. The problem is that the different disciplines use different modelling approaches and model descriptions. Moreover, within the disciplines, information and data with high degree of detail are needed. For the understanding of the overall system, it is crucial to extract that information from the detailed, discipline-specific information that is essential for the relevant system views. This condensed information can be the basis for the creation of system models that reflect the different views of the overall system.

The challenge is that the knowledge of the entire system does not equal the sum of the knowledge from the corresponding domains. This can simply be concluded from the fact that some properties (e.g. natural frequencies) of the overall system result from the interaction between the subsystems and cannot be derived from a separated analysis of all subsystems. The domain knowledge must therefore be generalized (abstracted) and integrated in order to gain the knowledge of the integrated system. Examples can be seen in [7], [8].

## 2.2. Definition of a System

The system environment is everything that is not within the system boundaries. The system boundary describes the limit of the system to its system environment, with which it has interfaces (e.g. energy or information or material). The system boundary is often not identical with the physical limits of a system or its components. The functions, inputs, and outputs of the system have to be distinguished from those of other systems, which is a pre-requisite to get clear definitions of interfaces and areas of responsibility. Conversely, if the system boundary is changed, also the object of investigation is altered and hence the view of the modified system has to be changed.

A subsystem is an element of a system that may contain of other elements. System elements are thus components (building blocks) of a super-ordinate system. The decomposition of the system into system elements and relations between them and the system environment creates a (hierarchical) structure of the system.

Inputs can be defined as external relations to the system (e.g. observations from the environment). Output parameters are the connection to the system environment like measurements, observations of the system or results of system actions.

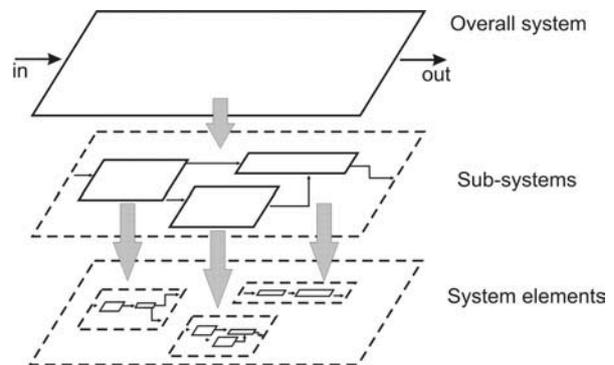


Figure 1. Hierarchical decomposition of an overall system [9]

The system structure includes a set of system elements as well as the quantity of relations between them and the system environment. Especially for complex systems, it is useful to define different viewpoints on a system (considering aspects such as geometry, location, staff, material flow, energy, etc.).

## 2.3. Autogenetic Design Theory

The Autogenetic Design Theory (ADT) applies analogies between biological evolution and product development by transferring the methods of biological evolution (and their advantageous characteristics) to the field of product development [11] [10]. Such characteristics are, for example, the ability to react appropriately to changing environments (requirements and boundary conditions), so that new individuals are in general better adapted to the actual environment as their ancestors. The ADT is not another variety of Bionics (where results of an evolution, e.g., the structure of trees, are transferred to technical artefacts). Rather, the ADT transfers procedures from biological evolution to accomplish both a description and broad support of product development with its processes, requirements, boundary conditions, and objects (including their properties).

The main thesis of the ADT is that procedures, methods, and processes of developing and adapting products can be described and designed as analogies to the procedures, methods, and processes of biological evolution to create or to adapt individuals. Main characteristics of biological evolution (with the underlying principle of trial and error) are continuous development and permanent adaptation of individuals to dynamically changing targets, which in general have to be accomplished in each case at the lowest level of energy content and with the minimal use of resources, i.e. the evolution process runs optimised in terms of energy consumption and resource employ-

ment. The targets can change over time because of (unpredictable) changing requirements, resources, conditions, boundaries, and constraints, and they can contradict each other at any time [12].

The result of a biological evolution is always a set of unique solutions having the same fitness value but not being of the same type. Consequentially, the result of the ADT is for the very most part a set of unique solutions that are equivalent, but not equal, and that fulfils the actual state of requirements and conditions best.

At the present state, three major components of the ADT have been researched. First, a process model describing how the ADT works and what the steps are, which the product developer has to perform. Secondly, the solution space model, which shows how the space, in which product development takes place, is structured. The third component is the underlying product model, which holds the description of how product information is structured and used.

Although the research on the ADT is ongoing, a subset of its methods has been implemented in an optimisation tool called NOA (Natural Optimisation Algorithm). At present, basic procedures and first approaches can be applied already. Due to its design, NOA can be used to solve any optimisation problem (e.g. improving of existing solutions while considering certain boundary conditions) as long as the object to be optimised can be described by means of parameters (not necessarily only geometric parameters). The general procedure of NOA can be seen in Figure 2.



Figure 2: General procedure of NOA

To receive the best results it is not advisable to run NOA completely autonomously. A designer is recommended to prepare the optimisation, monitor the progress of the optimisation, and to interpret the results of the optimisation. Prior to the optimisation, the designer has to prepare the scripts for the evaluation as well as the objective function, which calculates the fitness of every solution (individual). To establish a significant and suitable objective function, it is necessary to acquire sufficient knowledge about the system behaviour (e.g. by simulation) in order to implant the essential system properties into the objective function in a well-balanced relation.

During the optimisation, the designer is advised to observe the progress in order to ensure that the optimisation is heading into the desired direction. If not,

he has to reconfigure the optimisation (e.g. objective function, optimisation criteria, evaluation scripts). At the end of the optimisation, the designer has to check and interpret the results. Usually, NOA finds a set of equivalent but not equal solutions along a Pareto front, from which the designer can choose his (actually) preferred solution.

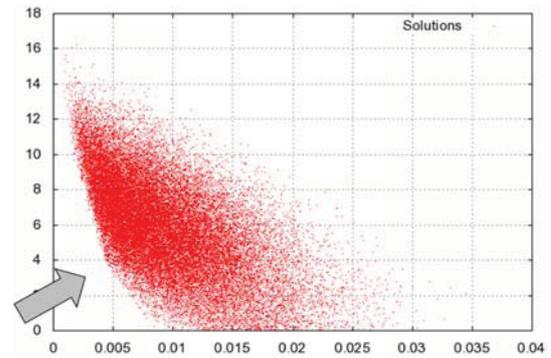


Figure 3: Pareto front

### 3. OPTIMIZATION PROBLEMS WITH REDUCED MODELS

From the viewpoint of system modelling, the system structure includes the set of system elements as well as the relations between them and to the system environment. In many cases, a very accurate system modelling is not reasonable, as uncertainties and costs of a quite detailed model may be so high that the drawbacks compared to a simpler model become significantly overbalanced. Models have to be clearly defined, in a consistent, compatible, and manageable way in order to become suitable, efficient, and easy to use for solving a specific task.

Parameters like inertia and electrical capacity depend on the sub-systems and they can only be optimized in common. Furthermore, the extensive functionality and complex structure of mechatronic systems amplify the effect that generally it is not sufficient to optimize just a single objective. In contrast, often a multi-objective optimization is needed.

The problem of optimizing an overall but detailed problem as a whole is that extensive considerations and detailed simulations from each involved discipline are required, which lead to extensive time requirements. Keeping this in mind, a method will be presented that applies reduced models for the optimization of the overall system.

### 4. APPLICATION

#### 4.1. Problem description

In a case study, the optimization of a drive train will be discussed. A drive train is used to transmit mechanical power from a drive motor to a load. A drive train is realized in various systems (e.g. from automotive engineering or in industrial plants). In this paper,

different drive concepts for a coiler/decoiler in a rolling mill are analyzed with respect to their dynamic performance, vibration behaviour, and mechanical strength of the drive shaft.

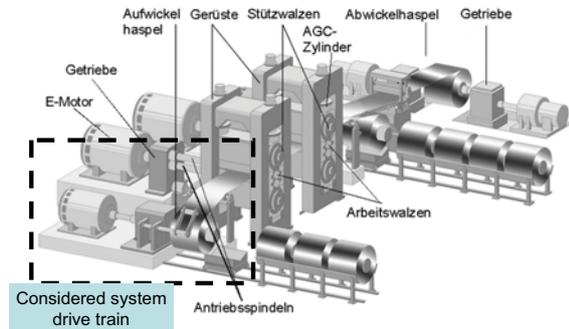


Figure 4. Rolling Mill [9]

In the first step, a detailed 3D CAD model was used to develop a reduced model of the drive shaft for a finite element analysis. For the application of system optimization, the model was reduced to a model with only few numbers of characteristic attributes (mass, moments of inertia, torsion stiffness of the drive train, etc.). To analyze the dynamic behaviour of the overall system, a numerical simulation model was developed from which a simplified analytical model is derived retaining the lowest eigenfrequencies of the more detailed model. The aim of the reduced system model is to optimize the system considering different parameter combinations of the drive section.

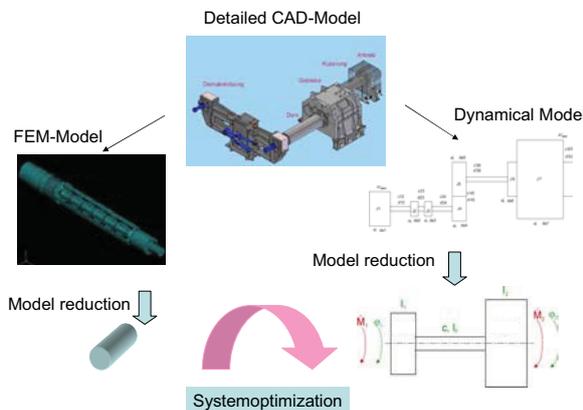


Figure 5. Model reduction [9]

#### 4.2. Optimization step

Within the optimization, a reduced analytical model is used to improve certain properties of the drive shaft. These properties are:

- Torsion stress  $\tau$
- Amplitude  $A_M$
- Mass of the shaft  $m_w$
- First eigenfrequency  $\omega$

The goal of the optimization is to reduce the torsion stress, the amplitude, and the weight, and to exceed a predefined first eigenfrequency.

Due to the simplicity of the reduced model, the complete optimization is done analytically with the use of NOA.

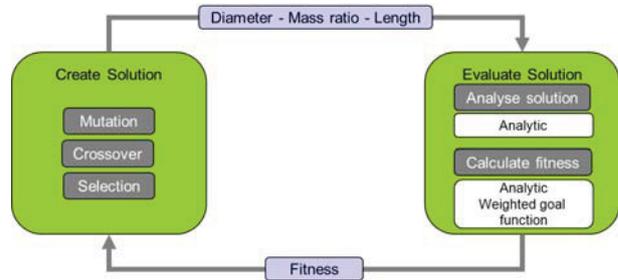


Figure 6: Optimization process

#### 4.3. Results

Various optimizations were performed to test different optimization setups. At the end, all performed optimizations came up with multiple solutions, which represent an improvement compared to the reference setup.

To verify the results of the optimization, a reference setup (based on an existing rolling mill) was used. This reference setup is characterized by the following parameters:

Parameter	Value
Diameter of the crank shaft	90mm
Mass ratio	50% / 50%
Length of the crank shaft	1500mm

These parameters result in a solution with the following properties:

Property	Value
Torsion stress $\tau$	83,66N/mm <sup>2</sup>
Amplitude $A_M$	6MNmm
Mass of the shaft $m_w$	85,4kg
First eigenfrequency $\omega$	1,09rad/s

In table 1 a few selected results are shown. NOA found many improved solutions (compared to the reference setup). Depending on the preferences for the different optimisation criteria, torsion stress, amplitude, weight and deviation from the target frequency, different solutions mark the optimum.

Table 1: Best solutions

Criteria	Overall best	2	3	4	5
Torsional stress $\tau$	83,66	78,3	83,66	83,66	83,66
Amplitude $A_M$	4872000	5280000	4800000	5064000	525600
Mass of the shaft $m_w$	80,87	84,82	82,49	75,79	85,46
Frequency $\omega$	1,14	1,18	1,14	1,18	1,10

In the opinion of the authors, the solution in the grey column is the overall best solution of the optimisation. This solution shows an improvement for all criteria and the target frequency of 1,09rad/s was only missed narrowly.

In row 2 to 5 the best solutions for each criterion are presented. It can be seen, that single criteria can be improved, if a negative impact on the other criteria is accepted.

## 5. CONCLUSION AND OUTLOOK

According to the increasing degree of detailing during the design process, the described models become more and more detailed; leading to a hierarchy of models as well as their describing parameters. For an optimization it is helpful to reduce this model. In this contribution the optimization was realized using the Autogenetic Design Theory. At the end of the paper the optimization of a drive train for a coiler/decoiler in a rolling mill will be discussed in more details. An open question is how the optimized solutions provided by the suggested system model correspond to optimized solutions yielding from an overall system model composed of detailed, discipline-specific models. This question is a matter of current research by the authors.

## 6. ACKNOWLEDGEMENT

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