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COMPARISON OF LOW- AND HIGH-FIDELITY APPROACH IN MODEL BASED DESIGN IN THE CASE OF A PORTABLE MOTION PLATFORM

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ABSTRACT

In this paper a low- and high-fidelity modeling approach was applied and compared in the case of design of a portable motion platform. In the low-fidelity design approach, a Design Analysis Tool was used for generating information about design sensitivity analysis and correlation of design parameters. In the high-fidelity design approach, the motion platform was designed using Matlab/Simulink/SimMechanics including the mechanical and pneumatic subsystem of the platform.
These approaches were compared in terms of required modeling effort to a relative error of predicted and measured system properties. The results of a low-fidelity model were achieved within one day whereas high-fidelity approach required three weeks of work. The relative error in low-fidelity approach was about 21-25 % and 4-6 % in high-fidelity modeling. Based on experiences achieved in this design case both of these modeling approaches were justified. Low-fidelity model can be seen especially important in early design phase when design alternatives were speculated with design constrains. High-fidelity model was useful on detailed design when dynamic properties of the system were considered more detailed.

Keywords: early design phases, product modelling, simulation

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1 INTRODUCTION

Model-based Product Design using computer simulation and functional prototypes has become a standard design practice in most companies in mechanical engineering. Simulation software tools such as Matlab/Simulink contain toolboxes that make it easy to model complex multidisciplinary entities. Such models can be considered as high-fidelity models as they include detailed models with a great number of parameters. In many cases, some parts of the entity need to be modelled in a very detailed way as modeling Toolboxes are not generic enough. A general observation in industrial design projects is that this approach takes a lot of time and that design supporting information is not easy to achieve especially in an early design phase when the most important decisions are made (Pahl and Beitz, 1988). The early design stage and the problem of suitable design tools are discussed in Marion *et al.* (2011), Kirisci *et al.* (2011) and Seppälä *et al.* (2011).

The traditional approach in an early design phase has been deriving simplified equations which give an explicit connection between the product properties and the design parameters. Such models are considered as low-fidelity models because they usually require some simplifications and heuristic modeling. Their drawback is typically low modeling accuracy but their benefit is their fast capability to provide design information. Different matrix methods for design analysis (Krus, 2006), (Krus, 2008) are useful for showing the mapping of relations between system parameters and system characteristics.

In this paper, a Design Analysis Tool for supporting a low-fidelity modeling approach is presented and applied in the case of the design of a portable motion platform. A portable motion platform is a relevant design example because it is a multidisciplinary device that includes six pneumatic actuators and an inverse Stewart platform mechanism. The Design Analysis Tool generates very valuable information for an early design phase providing a design sensitivity analysis, the correlation of design parameters, and design optimization. In order to facilitate the advantages and disadvantages of the low-fidelity modeling approach, a high-fidelity modeling approach is also applied to the design problem. The modeling approaches are compared in the sense of modeling accuracy, achieved design information and the effort of modeling the motion platform.

2 PORTABLE MOTION PLATFORM

Virtual technology is an important design tool in the development process of mobile machines and other human-machine interfaces. Vehicle simulators with a motion platform can provide a safe, convenient, and comprehensive environment for conducting research, development, training and the certification of human operators.

Motion platforms are often characterized by the range of motion, payload capacity, degrees of freedom (DOF), and types of actuators used to move the platform. A 6 DOF motion platform provides limited linear (x/y/z) and rotational (roll/pitch/yaw) motion. One popular design configuration is the Stewart platform or “hexapod” (Stewart, D., 1965–1966) which is a frame with six or more actuators connecting a fixed base to a moveable platform providing high load capacity, rigid, high precision and repeatable operation. In the “inverted hexapod”, the upper platform is secured to a frame and lower base can be moved. The simulators are usually equipped with hydraulic, pneumatic or electric actuators. Hydraulic actuators are powerful and relatively accurate but need an expensive and heavy fluid power unit. Electric systems provide good accuracy and controllability but their power to weight ratio is relatively low and the components are quite expensive. Pneumatic systems provide a high power to weight ratio and they are relative cheap and easy to use and maintain.

This paper describes the conceptual design of a low-cost and portable pneumatic motion platform for a vehicle driving simulator in virtual environments. The platform is driven by six pneumatic muscle actuators that provide very high force-to-weight characteristics (Figure 1).

The design of such a platform is complicated due to complex structure as well as several constraints that are related to the construction. The motive to design this motion platform was that suitable portable solution was not found on the market. The majority of motion platforms are realized with fluid or electrical power, which leads to too heavy construction. The need for portability comes from the fact that this device needs to be used in various locations and transferring it may not be too laborious. Another important need is the low-dimension construction because this device is meant to be used inside a Walk-in Virtual Environment without any change to the display system.

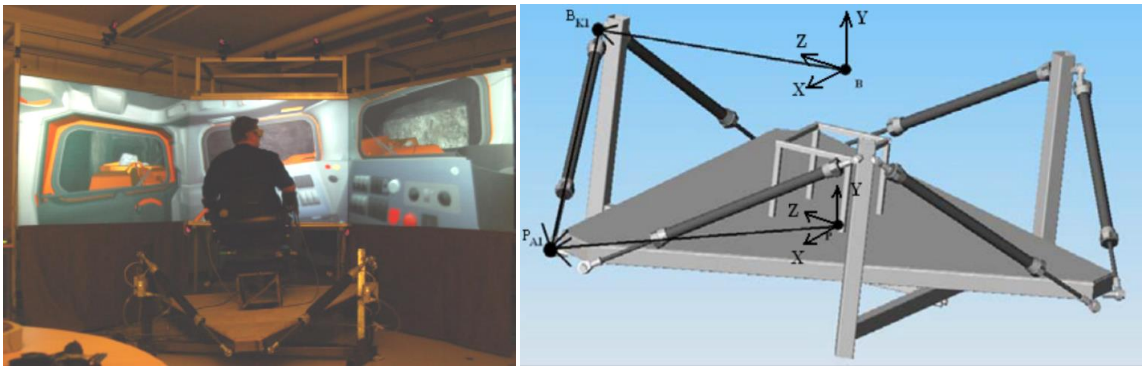

Figure 1. Virtual environment for vehicle testing and construction of motion platform

The main requirements for the platform were:

- **r1**: the platform needs to be portable so that at least two men can move and transport it
- **r2**: the platform needs to be low that it does not limit visibility in the simulator
- **r3**: the platform needs to small enough to fit inside the Virtual Environment
- **r4**: the platform needs to perform certain acceleration in the vertical (Y) direction
- **r5**: the platform needs to perform certain acceleration in the horizontal (X) direction
- **r6**: the platform needs to perform certain inclination

The Motion platform is used to mimic motion in a Cockpit of Mobile Work Machine which set certain values for acceleration in the vertical (Y) and in the horizontal (X) directions. Furthermore, the inclination of the platform needs to reach a certain value.

The inverse Stewart-platform was taken as a basis because it allows a low dimension and simple construction. Pneumatics was selected as the actuator technology due to its low weight and low cost. Furthermore, pneumatic muscle actuators were used due to their high force/weight ratio.

3 DESIGN OF A PORTABLE MOTION PLATFORM

The Stewart-platform is a complex structure whose kinematics cannot be solved in an explicit form (Egner, 1996). The design of such a device is challenging due to its complex structure and actuator technology as well as the fact that there are several constraints that need to be fulfilled.

The structure of the Stewart-platform is typically presented with two circles describing the fixed and mobile plate and the location of the actuator joints, Figure 2. Symbol r is the radius of the actuator joints in the structure and R is the radius of the actuator joints in the motion platform. Symbol h is the distance of the actuator joints in the vertical direction. Symbol β is an angle which is due to symmetry 60°.

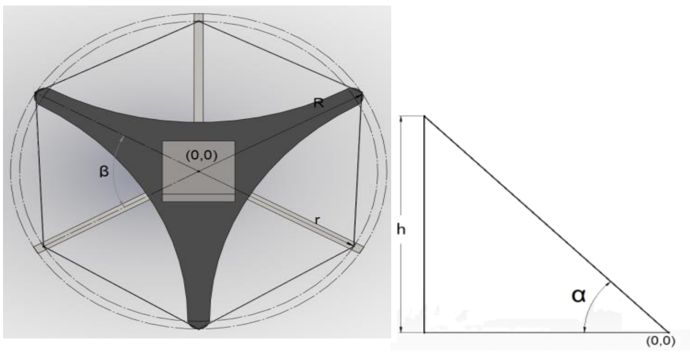

Figure 2. Structure and main parameters of an inverse Stewart-platform

3.1 High-fidelity modeling

Model-based engineering (MBE) applies high-fidelity predictive models in combination with observed data to the engineering process in order to explore the design space as fully and effectively as possible and to support design and operating conditions. In order to create a high-fidelity predictive model, it is often necessary to combine theoretical knowledge and empirical information derived from real-world experiments. In our case, this involves writing equations for mass flow, pressure, and the force dynamics of the control valve – muscle actuator combination. The key objective is to arrive at a model that is accurately predictive over a range of scales and operating conditions. The high-fidelity model can be used to optimize many different aspects of design and operation**,** such as to accurately determine optimal designs and to predict performance in many operating conditions, to troubleshoot poor performance, to perform online monitoring, to perform a control design, etc. A good model can be used to explore a much wider design space than it is possible using simpler design approaches.

A high-fidelity model of the motion platform is developed using the Matlab/Simulink and SimMechanics modeling toolboxes. SimMechanics allows engineers to model complicated mechanical systems, simulate and analyze the models, and develop controllers for the mechanical systems. SimMechanics is used to model the mechanical components of a system, and Simulink is used to model the pneumatics (valves, actuators) of a system as shown in Figure 3. The rigid bodies of the platform are modeled using Body blocks that are connected to each other using Joint blocks. The mechanical components of the motion platform consist of a base plate, a mobile plate, and six legs connecting the mobile plate to the base plate. Each leg subsystem contains two bodies (as the muscle actuator is modeled as a cylinder) connected together with a cylindrical joint. The lower actuator body is connected to the mobile plate using a universal joint, and the upper body is connected to the bar of the base plate using a second universal joint. Overall, the mechanical model of the system consists of 22 body blocks and 36 joint blocks. Each body block needs a defined coordinate system for the center of gravity as well for as the mass and inertia. The specific geometry of the system in its initial configuration and the dynamic parameters for the platform are written in a basic Matlab script.

The pneumatic model consists of models of control valves and muscle actuators. The model of the control valve transforms the valve command signal into a mass flow rate. The muscle actuator model receives the mass flow rate as an input and outputs the effective force of the actuator for the SimMechanics model. The actuator model includes the pressure dynamic equation of the actuator, the nonlinear force generated by the actuator as a function of actuator pressure and displacement, the damping/viscous friction of the actuator, as well as the static friction of the mechanism. The parameters for the model are estimated analytically and semi-empirically.

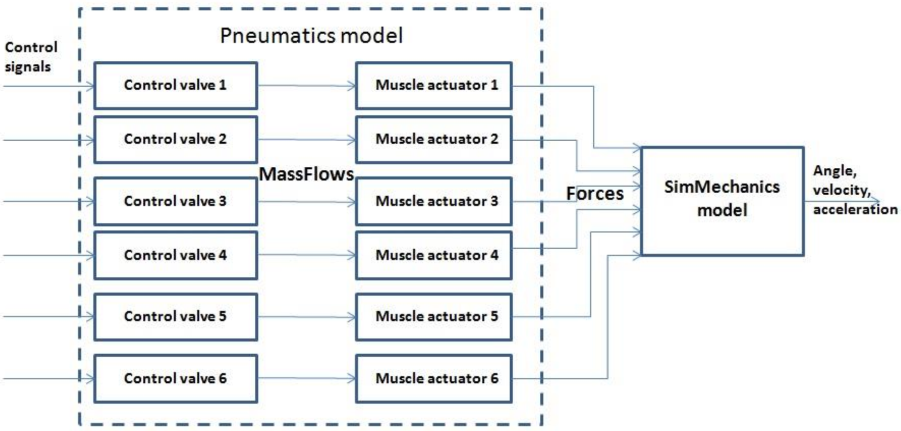

Figure 3. High-fidelity model in Matlab Simulink/SimMechanics

With the resulting model, the system can be easily simulated to find out whether it fulfills the required performance characteristics (e.g. angle, acceleration). In the first phase, the system can be studied with the SimMechanics model only by applying input forces to the mechanism. In this way, the forces required by the actuators can be defined to meet the required performance. Also, at this phase it is convenient to analyze the system by simulations with different sets of design parameters (e.g. radius of the base and mobile plate, height of the platform). However, this would require many simulation runs based on which a sensitivity analysis can be performed. In order to provide more realistic results of the performance of the system, the pneumatics model is added to the simulation. At this phase, it can be verified whether the chosen actuators can provide sufficient force and the chosen valves can provide enough mass flow to meet the required dynamical requirements. Also, the full high-fidelity model provides a good tool for controller design and testing different control approaches.

3.2 Low-fidelity modeling

A simplified low-fidelity model is defined by studying the platform in steady state operating points with minimum, maximum and medium control signals. With the minimum control signal, the actuators are unpressurized (actuator in maximum length) and the platform is in its lowest position. With the maximum control signal, the actuator is fully pressurized (length 80 % of maximum) and the platform is in its highest position. The platform is designed to operate around the medium control signal while the actuators are in their medium position. Using simple trigonometry and force equations (Jouppila et al., 2011) it is possible to write explicit equations for the system characteristics of the motion platform: vertical acceleration a_y, horizontal acceleration a_x and maximum inclination ω_{max} as a function of the main design parameters r, R and h

$$a_y = \frac{6 F_a \sin(\alpha_{mid}) - m g}{m} \tag{1}$$

$$a_x = \frac{2 F_a \cos(\alpha_{mid})}{m} \tag{2}$$

$$\omega_{\max} = \tan^{-1}\left(\frac{h_{\max} - h_{\min}}{R + r}\right) \tag{3}$$

where F_a is a maximum force in a single actuator, m is the mass of the motion platform and g is a gravitational constant. The maximum actuator force F_a is defined from characteristic curves in the manufacturer data sheet (Festo, 2002) within 50 per cent supply pressure. Because muscle actuators are able to generate only a pulling force, we assume that horizontal acceleration is created by two actuators.

The low-fidelity model described above is a steady state model that can map the main design parameters to the system characteristics at the operation point. However, it cannot model the operation of the device or support the design process in a more detailed phase.

3.3 Design Analysis Tool

In design, matrices can be used to describe the relationship between some design parameters that are to be determined and some aspects of system behavior. Notation design parameters are used by Suh (1990). Here, the term design parameter is used for parameters that can be manipulated by design; these are a subset of system parameters that represents all parameters that describe the product. The behavior of the system is called functional requirements, FR, by Suh. Here, the notation system characteristic is used. This is a little broader because it covers all the aspects of behavior and properties of the product.

3.3.1 Design Matrices

The relationship between input variables and output variables can be written as:

$$\mathbf{y} = \mathbf{A}\mathbf{x} \tag{4}$$

where $\mathbf{A}$ is a matrix and $\mathbf{x}$ is a vector that is mapped into $\mathbf{y}$ through $\mathbf{A}$. This assumes linear relationships to be true. For non-linear systems, such a relationship is still useful as a linearized representation that can be used around a point of interest. Here, sensitivity analysis can be used to obtain the sensitivity matrix for small variations around a nominal set of parameters. Sensitivity analysis can be used to give a quick overview over what parts of the design are important for the desired behavior. Sensitivity analysis is the primary tool for studying the degree of robustness in a system. Assuming the system:

$$\mathbf{y} = \mathbf{f}(\mathbf{x}) \tag{5}$$

where $\mathbf{f}(\mathbf{x})$ is a nonlinear function. However, using linearization around a nominal point, this can be written as:

$$\mathbf{y_0} + \mathbf{\Delta y} = \mathbf{f}(\mathbf{x_0}) + \mathbf{J}\mathbf{\Delta}x \tag{6}$$

where $\mathbf{J}$ is the Jacobian matrix, where

$$J_{ij} = \frac{\partial f_i(x)}{\partial y_j} \tag{7}$$

hence $\Delta\mathbf{y} = \mathbf{J}\ \Delta\mathbf{x}$. The Jacobian **J** is also identical to the sensitivity matrix **K.** The elements in the sensitivity matrix can therefore be expressed as:

$$k_{ij} = \frac{\partial y_i}{\partial x_j} \tag{8}$$

3.3.2 Normalized Sensitivities

If the system is complex, and the sensitivity matrix is large, it may be difficult to get an overview of the system because the different parameters may have values of different orders of magnitude. The system characteristics are normally also of different orders of magnitude. In order to make it easier to get an overview of the sensitivities, some kind of normalized dimensionless sensitivity is needed. The first approach to normalize the sensitivities is to employ the following definition.

$$k_{ij}^0 = \frac{x_{s,j}}{y_{s,i}} \frac{\partial y_{s,i}}{\partial x_{s,j}} \tag{9}$$

In this way, a non-dimensional value is obtained, which indicates how many per cent a certain system characteristic is changed when a system parameter is changed by one per cent. In this way, it is much easier to assess the relative importance of the different system parameters.

3.3.3 Functional Correlation

In a design, the different system characteristics may be conflicting or more or less pulling in the same direction. Information about this is very useful when setting up the requirements for a design, since it can show what areas that can be improved without sacrificing too much in other areas, or to see what areas might be worth sacrificing in order to improve others. A simple measure of this is the functional correlation matrix, $\mathbf{C_F}$. Here, each row of sensitivities is seen as a vector, and the correlation between them is simply a measure of how aligned two vectors are. This uses the correlation coefficient. The correlation coefficient between two system characteristics is defined as:

$$C_{F,ik} = \frac{\frac{1}{n}\sum_{j=1}^{n} k_{ij}^0 k_{kj}^0}{s_i s_k} \tag{10}$$

Here, the standard deviations in the sensitivities are:

$$s_i = \sqrt{\frac{1}{n}\sum_{j=1}^{n}\left(k_{ij}^0\right)^2} \tag{11}$$

Adjusted correlation is obtained if they are multiplied with the sign φ of the desired direction for a system characteristic, so that if a large value is desirable, or required, $\varphi = 1$ and if a small value is desirable, or required, $\varphi = -1$.

$$C_{AF,ik} = \varphi_i \varphi_k \frac{\frac{1}{n}\sum_{j=1}^{n} k_{ij}^0 k_{kj}^0}{s_i s_k} \tag{12}$$

3.3.4 Design Optimization

Consider the following optimisation problem. The system characteristics **y** are computed from the system parameters $\mathbf{x_s}$

$$\mathbf{y} = \mathbf{f}(\mathbf{x_s}) \tag{13}$$

The objective function is in general a function of system characteristics and system parameters (can also be defined as a separate system characteristic). The objective function is a function of the system characteristics.

$$f_{obj} = g(\mathbf{y}) \tag{14}$$

It is most often practical to express the problem as a minimization problem where the total objective function is expressed as a sum of sub-objective functions that are related to all system characteristics. A useful formulation is

$$f_i = w_i P_i \left(\frac{y_t}{y + \varepsilon} \right)^{\varphi\gamma} \tag{15}$$

where φ is equal to one, if the system characteristics should be maximized and minus one otherwise. The quotient y_t/y represents the degree of “unfulfilment”, ε is a very small number that should prevent singularity, w_i are weights based on the priorities of the system characteristics priorities, and γ is an additional exponent that normally is set to γ =2.

3.3.5 Design Analysis Tool

The implementation of the design analysis tool can be realized with many CAD-tools. In this paper, the tool was implemented in Excel, which is widely used in early design calculations, providing useful tables for displaying relationships between different quantities. The tool contains features for sensitivity analysis, functional correlation and design optimization. The optimization algorithm is realized with a Complex algorithm (Box, 1965) and the lower and upper limits can be given to the design parameters to be optimized.

The system models can be implemented in their own Model Tab directly in an Excel or Visual Basic script. Furthermore, models of arbitrary fidelity can be connected externally. The user interface of this Design Analysis tool is shown in Figure 4.

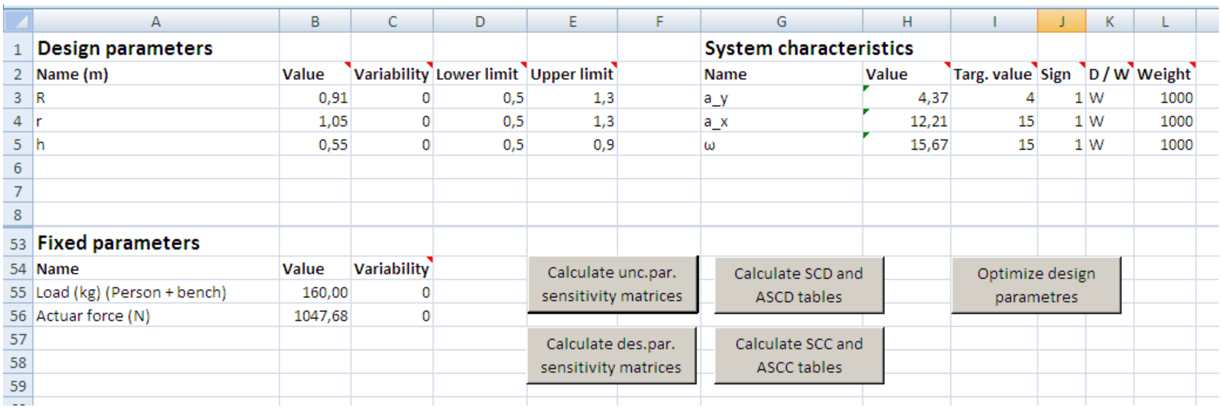

Figure 4. User Interface of the Design Analysis Tool

The normalized sensitivity matrix and the adjusted system characteristics correlation table for a portable motion platform are presented in Table 1. These tables give a lot of information about the design opportunities. From the system characteristics correlation table, we can see that the horizontal a_x and vertical a_y accelerations are basically opposite system properties (shown in red color in the correlation table). Therefore, increasing one such property would decrease another. Also, maximum inclination ω_{max} is opposite to a_x but in line with a_y.

The normalized sensitivity matrix describes how sensitive the design characteristics (vertical/horizontal acceleration and max. inclination angle) are to changes in the design parameters R, r and h. The sensitivity matrix is used to find an optimal set of design parameters to satisfy the characteristics requirements. If e.g. higher vertical acceleration a_y was required, it could be achieved by increasing platform height h or decreasing radius r and R. Parameter h would be the most useful parameter as it only slightly decreases horizontal acceleration a_x and would substantially increase vertical acceleration. Furthermore, it would increase the maximum inclination angle ω_{max}. The next option would be reducing the value of parameter *r* which leads to similar but less sensitive consequences.

Table 1. Normalized Sensitivity matrix and adjusted system characteristics correlation table.

Normalised sensitivity matrix of the design parameters

		R	r	h
	Actual value	0,91	1,05	0,55
a_y	4,37	-0,98	-1,75	2,73
a_x	12,21	0,05	0,08	-0,13
ω	15,67	-0,44	-0,51	0,95

Adjusted system characteristics correlation table (ASCC)

		a_y	a_x	ω
	Actual value	4,37	12,21	15,67
a_y	4,37	1,00	-1,00	0,99
a_x	12,21		1,00	-0,99
ω	15,67			1,00

The Design Analysis Tool makes it possible to study design alternatives in an efficient and comprehensive way. This is especially useful if the target values for system properties are not exact.

4 COMPARISON OF THE LOW- FIDELITY AND THE HIGH-FIDELITY MODELING APPROACHES

Comparison of two different modeling approaches is complicated because it is firstly dependent on both the user's sophistication in using the simulation tools and their knowledge of the specific technologies needed to model in the considered case. Secondly, modeling is affected by how well the simulation model library supports the case under study. In many practical cases, part of the model includes some specific entities that need to be modeled from basic equations. In our case, the pneumatic system with muscle actuators is such a specific entity that it is usually not found in model libraries. In this study, the modeler has a good knowledge of the simulation tools and technologies used.

The modeling effort for both approaches is evaluated by the number of equations that need to be programmed, the number of parameters that need to be identified, the time required to create the model, and the time needed for analyzing the model. The results are shown in Table 2.

Table 2. Effort for using the model based analysis

	Low-fidelity model	High-fidelity model
Number of model equations	14	30 eqs. + 58 SimMech. blocks
Number of model parameters	10	270
Time required for creation the model [h]	7	120
Time required for analyzing the model [h]	1	16
Expertise needed in modeling	Low	High

The drawback of high-fidelity modeling is evidently the large number of equations and parameters. In this particular case, the number of equations and parameters in the high-fidelity model is reduced due to the similarity of the pneumatic actuators and valves. In the low-fidelity model, the number of model equations and parameters is considerably smaller compared to high-fidelity models.

The main difference between these approaches is time required for creation the model. The low-fidelity model was accomplished during one day whereas about three weeks it were needed to accomplish the high-fidelity model. The required time for creating the model and timeframe available for the early design phase is naturally case-dependent.

The high-fidelity simulation model typically allows simulating different responses, such as step and ramp. Although modern PC's can simulate them fast, refining this information to support actual design, such as sensitivity analysis, takes time.

The accuracy of design information is naturally dependent of the fidelity of the model. Table 3 presents the accuracy of the studied product properties in the case of the low- and the high-fidelity models. These results are compared to measured values indicating the relative error in modeling,

Table 3. Accuracy of the model-based analysis

Measured value		Low-fidelity model		High-fidelity model	
		Actual value	Relative error	Actual value	Relative error
a_y	3.6 m^2/s	4,37 m^2/s	21 %	3.75 m^2/s	4 %
a_x	9.0 m^2/s	12,2 m^2/s	25 %	9,45 m^2/s	6 %
ω_{max}	16 ˚	15,7˚	2 %	16,3˚	2 %

In the low-fidelity model, the relative error in product properties a_y and a_x was 21 to 25 per cent. Such accuracy is acceptable in an early design phase. In the high-fidelity model, the relative errors were 4 to 6 percent, which is suitable accuracy for the detailed design phase. The product property ω_{max} was calculated more precisely with the relative error of 2 per cent in both cases. This is due to the nature of the model, which makes it easy to calculate this value.

5 CONCLUSIONS

In this paper, a Design Analysis Tool for supporting the low-fidelity modeling approach was presented and studied in a practical design case of a portable motion platform. The design information of the low-fidelity model can be significantly extracted by a Design Analysis Tool realized in MS-Excel, which makes it fast and easy to analyze system properties. The tool results in a normalized sensitivity matrix of the design parameters and an adjusted system characteristics correlation table, which give a lot of information for supporting the design.

For comparison, a high-fidelity modeling approach was realized using Matlab Simulink/SimMechanics toolboxes. The modeling approaches were evaluated and compared by the number of equations needed to be programmed, the number of parameters needed to be identified, time required to create the model, time needed for analyzing the model, and the accuracy of the model. The results indicate that the high-fidelity approach is capable of providing a very accurate model (relative error 4–6 %) at the cost of time (136 h) used for identifying the system parameters, analyzing and creating the model. As such, the high-fidelity model is very useful in a detailed design process phase, providing e.g. the validation and verification of design solutions by simulations. In this example case, the low-fidelity model was achieved within one day with a reasonably small number of equations and parameters. The relative error of low-fidelity approach was about 21–25 per cent, which is reasonable for use in the early design process. Also, the use of the low-fidelity approach does not require high-level expertise in modeling as the high-fidelity approach does.

Both the low-fidelity and the high-fidelity modeling approaches were justified. The low-fidelity model is especially important in the early design phase, when speculating about design options in view of design constrains. The creation and identification of the high-fidelity model often requires too much time that it could be used in an early design phase. The low-fidelity model is capable of providing sufficiently accurate initial parameters for use in the high-fidelity model for considering the dynamic properties of the system in more detail.

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