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Approach to Support Frontloading in Product Development by Cross-Domain Simulation Models for the Prediction of System Performance under Consideration of Relevant Thermal Effects

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Abstract

The prediction of the system performance of electrohydrostatic actuators (EHA) is often made with cross-domain simulation models with lumped parameters. Their main focus is on the mechanical, electrical and hydraulic power flow. Very often temperature dependencies of parameters are neglected due to a lack of system knowledge and complicated thermal interactions. A prediction of the dynamic behavior of systems under strong thermal effects, such as an EHA, might not be reliable enough if temperature dependencies and their effects are not considered.

A typical approach is to guess the temperature of the system based on the experiences of previous product generations. These experiences might not be transferable when significant changes in those systems are made. Another approach is to use a lumped-parameter thermal network simulation model, which requires system knowledge to approximate the heat transfer coefficients and thermal resistances. This system knowledge is often not yet available in the early stages of product development.

Therefore, this contribution aims to describe an approach that uses the combination of a basic cross-domain simulation model with lumped parameters and a conjugate heat transfer (CHT) simulation model. The determination of temperatures in the CHT simulation model enables the parameterization of the temperature-dependent parameters for the cross-domain simulation model. This allows the relevant thermal effects to be taken into account when predicting the system performance of the EHA.

The approach describes how the resulting power losses for a given load case are estimated and how the resulting heat sources are determined. These resulting heat sources are used as boundary conditions in the CHT simulation.

The CHT simulation simulates the involved thermal phenomena and the resulting temperature distribution throughout the system. The resulting temperature distribution can be used to parameterize the values of the lumped parameters in the cross-domain simulation model. The cross-domain simulation model is tested again with the adjusted parameters.

To evaluate this approach, the simulated dynamic behavior of the EHA is considered at different ambient temperatures. It was demonstrated that by using the described approach, the temperatures in the system could be estimated and thus the temperature-dependent parameters could be parameterized accordingly. The influence of the temperature on the system performance can therefore be taken into account in the cross-domain simulation model. This can reduce uncertainty in the early stages of product development and support the frontloading in product development.

1. Introduction

Early phases of product development processes have the inherent problem that they require engineers to make decisions for future development without having specific data or physical prototypes yet. One possibility to overcome this challenge is to use simulation models. This strategy is also called frontloading and thus provides methods to solve such problems [1].

Electrohydrostatic actuators (EHA) are used for safety-critical applications of primary flight controls. The integral design of the EHA poses new challenges for product development [2]. The prediction of system performance of the EHA is often made with cross-domain simulation models with lumped parameters. In most simulation models of the EHA, the main focus is on the mechanical, electrical and hydraulic power flow. Very often temperature dependencies of parameters are neglected due to a lack of system knowledge and complicated interactions [3–5]. The influence of the thermal domain on the mechanical and electrical parameters is getting more relevant due to increasing power densities [6]. The EHA must work reliably over a temperature range from -65°C to 100°C [7]. Accurate prediction of the dynamic behavior of systems under strong thermal effects lacks reliability if temperature dependencies and their effects are not considered.

A typical approach to incorporate thermal dependencies into a cross-domain simulation model is to guess the temperature of the system based on the experiences of previous product generations [3–5]. These experiences might not be transferable when significant changes in those systems are made. Additionally, the temperature-dependent parameters are not adjusted according to the current temperature [3–5].

Another approach is to use a lumped-parameter thermal network simulation model or other types of thermal simulation models [8–13]. This requires system knowledge to approximate the heat transfer coefficients and thermal resistances. This system knowledge is often not yet available in the early stages of product development. Conjugate Heat Transfer (CHT) simulation models are able to calculate the temperature distribution without having specific heat transfer coefficients. Within a CHT simulation model, all kinds of heat transfer, namely advection, diffusion and radiation are modeled [14].

Therefore, this contribution aims to describe an approach that combines a basic cross-domain simulation model with lumped parameters and a CHT simulation model. The described approach is shown in a case study using the example of an EHA. The determination of the temperature in the CHT simulation model enables the parameterization of the temperature-dependent parameters for the cross-domain simulation model. This allows the relevant thermal effects to be taken into account when predicting the system performance of the EHA. It can reduce uncertainty in the early stages of product development and support the frontloading in product development.

2. Materials and Methods

This chapter describes which materials and methods were used to achieve the research aim. First, the electrohydrostatic actuator (EHA) is presented. This is followed by the initial description of the approach that is carried out. Chapter 2.3 describes the basic cross-domain simulation model of the EHA with lumped parameters required for this approach. The CHT simulation model of the EHA, which is needed for the determination of the temperature curves, is described in detail in chapter 2.4. The load case of the EHA to evaluate this approach is specified in chapter 2.5.

2.1. Electrohydrostatic Actuator (EHA)

The EHA converts electrical power into an axial movement. They are used for safety-critical applications of primary flight controls. In contrast to conventional servo-hydraulic actuators, the EHA is an integral unit and is therefore under strong thermal effects due to its high power density [6].

In Figure 1 the components of the EHA (AHP Merkle, Type: EAHP BAS.50/32.U04.201.200 MI.BA100.G2.P42) are depicted. The EHA consists of a double-acting hydraulic cylinder, a supply piping system, an internal gear pump and a permanent-magnet synchronous machine. The change in the volume flow is thus continuous and is not affected by influences from the valves.

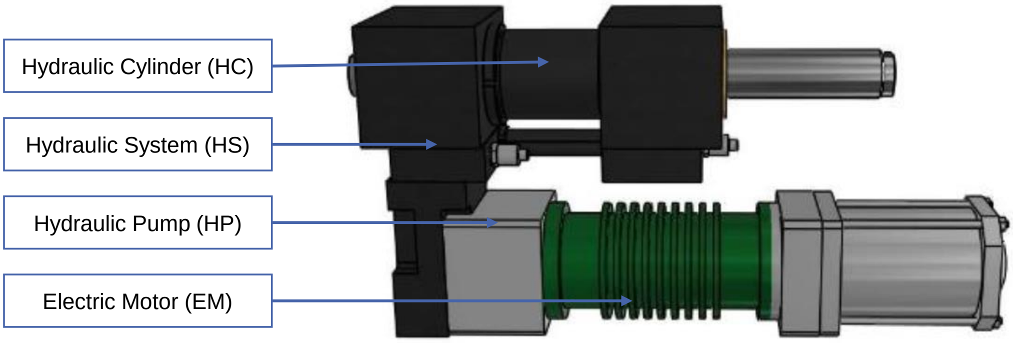

Figure 1: Structure and components of the electrohydrostatic actuator (EHA) [15]

2.2. Approach with the Combination of a Basic Cross-Domain Simulation Model with Lumped Parameters and a CHT Simulation Model

The approach is described in five steps and is shown in Figure 2. In the first step, the cross-domain simulation is used to determine the heat sources generated by power losses. In the second step, the heat sources of the individual subsystems are implemented as boundary conditions in the CHT simulation. The CHT simulation is run in the next step and calculates the temperature distribution of the steady-state. In step four, the average temperatures of the relevant components are determined. In the last step, those temperature-dependent parameters are adjusted according to applied temperature.

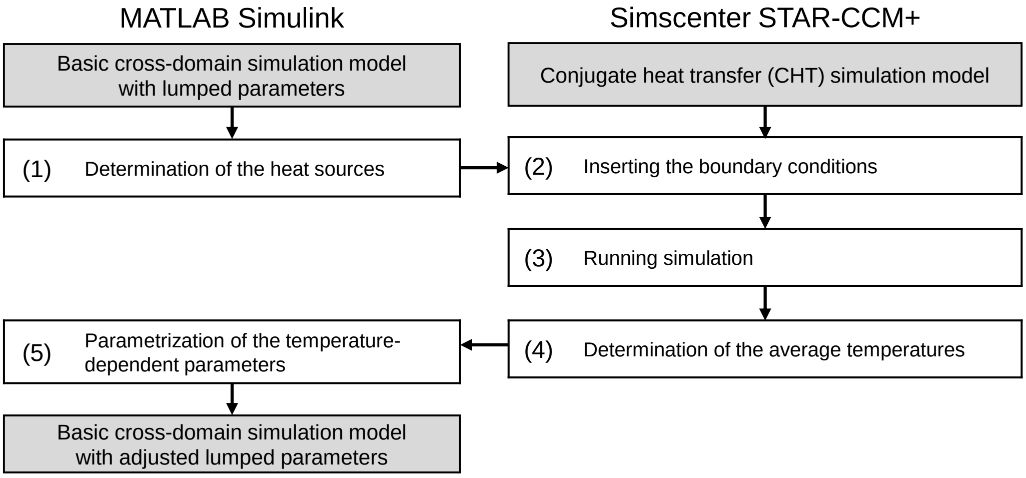

Figure 2: Approach with the combination of a basic cross-domain simulation model with lumped parameters and a CHT simulation model

The approach is applied using the example of the EHA. The structure of the cross-domain and the CHT simulation model of the EHA is described in more detail below.

2.3. Basic Cross-Domain Simulation Model with Lumped Parameters

The primary function of this simulation model is to prove the functional fulfillment and system reliability. The function to be investigated is the dynamic behavior of the deflection of the hydraulic cylinder.

Since the used variables for this simulation model are only functions of time and are not dependent on the spatial coordinates, modeling with lumped parameters is sufficient for this application. The simulation is therefore based on cross-domain modeling, in which the mechanical, electrical and hydraulic domains are considered to describe the dynamic system behavior. The software used is MATLAB® Simulink® (R2021a). Subsystems based on their function are created. Those can be described with the process elements transformer, converter, source and sink. Between those subsystems, the power variables are exchanged. For the electrical power, it is the current I and voltage U, for the rotational mechanical power, the torque M and rotational speed n, for the translational mechanical power, the force F and speed $\dot{x}$ and for the hydraulic power, the pressure p and flow rate $\dot{V}$. Additionally, the control unit uses the position x to set the rotational speed n.

Figure 3 shows the subsystems of the simulation model at the top level of the description.

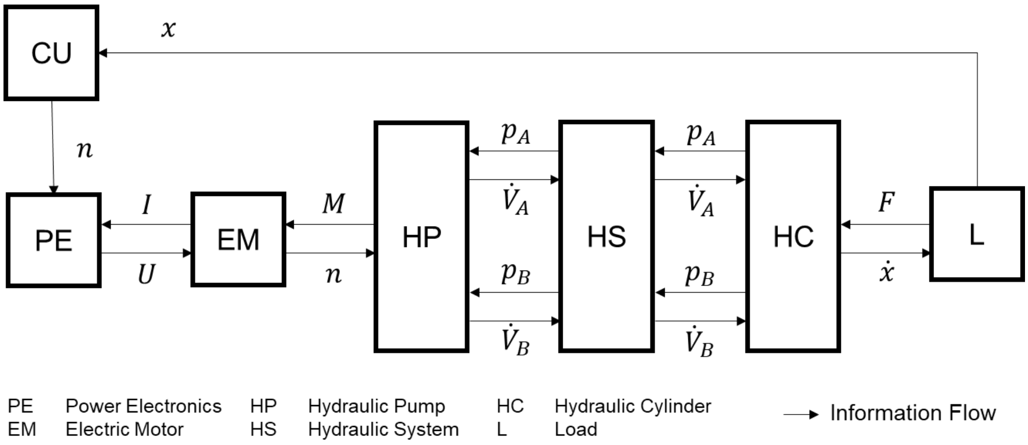

Figure 3: Interfaces between the individual subsystems of the EHA

In the following, the individual subsystems are briefly described. It is specified which physical effects are taken into account or are neglected.

Power Electronics (PE) and Electric Motor (EM)

The permanent magnet synchronous machine (PMSM) is shown as a reduced single-phase DC model. The temperature-dependent parameters of the electric motor can be reduced to the current heat losses in the copper windings in this case. The power electronics is only considered as a controlled system of a cascaded control of current and rotational speed. The losses of the power electronics are excluded in this simulation model.

Hydraulic Pump (HP)

The hydraulic pump is represented by white box modeling. The correlation between mechanical and hydraulic energy is done by a data sheet provided by the manufacturer. The hydraulic pump is an internal gear pump. The pulsation is not modeled. The compressibility of the hydraulic fluid is also neglected in this subsystem.

The leakage is determined by describing it as a laminar choke, which according is the simplest model of volumetric losses [16]. A leakage coefficient is used, which is dependent on the kinematic viscosity.

Hydraulic System (HS)

The hydraulic system has no valve control. Therefore, it consists only of the supply pipes between the hydraulic pump and cylinder. This means that the subsystem is characterized only by the losses of the pipe friction and the pipe elbows. The pipes are considered stiff and the compressibility of the hydraulic fluid is neglected due to the small amount of hydraulic fluid within the pipes compared to the overall system. Therefore, the capacity and inductivity of the pipes are not considered.

The pressure losses are dependent on the drag coefficient, which is determined differently for pipe friction and the pipe elbow. In the case of pipe friction, the drag coefficient is determined via the pipe friction coefficient, which depends on the Reynolds number. This depends, among other things, on the kinematic viscosity. The drag coefficient of the pipe elbows is determined empirically. There is also the dependence on the Reynolds number and thus on the kinematic viscosity.

Hydraulic Cylinder (HC)

The hydraulic cylinder is double-acting. The modeling is based on the description of Glöckler [17]. In this system, due to the high pressures and large volumes, the compressibility of the hydraulic fluid is taken into account. The stiffness of the oil column in the cylinder depends on the bulk modulus of the hydraulic oil. The losses that are modeled in this subsystem are the internal leakage and friction losses. The friction losses are modeled after Beater [16]. The internal leakage is based on the modeling of the hydraulic pump but also considers the pressure dependence.

Load (L)

The load model is assumed to be strongly idealized. A spring-damper system connected in parallel generates an applied force depending on the deflection or speed of the hydraulic cylinder. The spring rate is 100 kN/m, which is forceless at a deflection of 0 mm and increases with positive deflection. The damping coefficient is 1000 Nm/s.

2.4. Conjugate Heat Transfer Simulation Model

A conjugate heat transfer (CHT) simulation model of the EHA is used to determine the resulting temperatures during a specific load case. In this simulation model, the convective heat transfer, diffusive heat transfer and radiative heat transfer between and within the subsystems are modeled. Simcenter STAR-CCM+ by Siemens is used to simulate all kinds of heat transfer within one simulation model.

The aim of the CHT simulation model within this publication is to increase the quality of the parameter estimation for the simulation model presented in chapter 2.3. For this reason, detailed temperature distributions within each subsystem are not necessary, since an average temperature will be used for the lumped parameter simulation model. A coarse level of detail of the simulation model is sufficient to derive temperatures for the lumped parameters. Since the timescale of thermal diffusion within the system is a lot higher than the timescale of the piston movement, we neglect the flow of the internal hydraulic fluid in the CHT simulation. This allows us to run a steady simulation, which greatly reduces the computational effort. This assumption however is valid only for small movements of the piston, as are considered in this work.

The outer geometry of the EHA was provided by the manufacturer. The validity of the geometry data was checked through measurements on the EHA. The level of detail of the internal motor was chosen such that a distinction between rotor and stator can be made. Since the given geometry data did not include internal geometries, we created the internal geometry for the rotor and stator based on typical values for motors of this application. The inner radius of the rotor and stator were each chosen as 0.6 times the corresponding outer diameter. A fluid gap of 1.4 mm exists between the rotor and stator. The length of the internal geometry was chosen such that it coincides with the length of the cooling fins on the motor housing. The resulting internal geometry of the motor can be seen in Figure 4.

The geometry of the hydraulic pump was not specifically modeled, since only its heat input into the system is relevant. To enable this, a designated area where the pumps heat losses are entered into the system was defined.

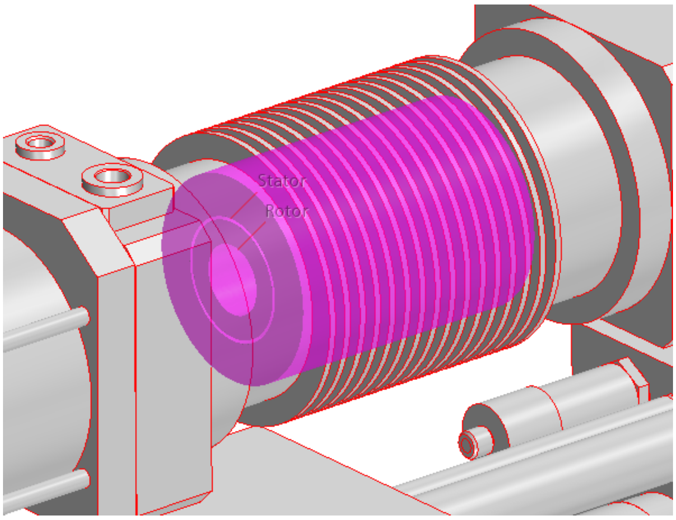

Figure 4: Motor housing with the internal geometry consisting of rotor and stator highlighted in pink.

The environment is modeled as a volume of air surrounding the EHA. The heat generated within the EHA is transferred through diffusive heat transfer to the EHAs surface. Natural convection in the immediate vicinity further transports the heat away from the EHA. The walls of the environment are subject to a fixed temperature, where the heat entered into the EHA leaves the simulation domain again. Radiative heat transfer between the EHA and the surrounding walls is considered.

Within the whole simulation domain, a Finite-Volume mesh was created with polyhedral cells. Boundary layer meshes were added on surfaces of fluid regions where convective heat transfer occurs. For the mesh within the EHA, a target cell size of 10 mm was chosen. In areas of surface curvature, or where small geometric details are present, the cell size reduces to 2 mm. For the surrounding air, the target cell size was set to 100 mm. For increased numerical accuracy at the boundary between the EHA and the surrounding, the surface cells are sized the same.

2.5. Considered Load Case

A load case with the sinusoidal speed with a frequency of 0.5 Hz and an amplitude of 150 rpm is considered. The initial deflection is 50 mm and therefore has a force of 5 kN at the initial time. To illustrate the influence of temperature, the three different ambient temperatures -65 °C, 20 °C and 80 °C are considered. These are based on the typical values for aircraft certification [7].

3. Applied Approach using the EHA as an Example

In the following, the approach presented in chapter 2.2 is applied to the example of the EHA. The simulation models from chapters 2.3 and 2.4 are used for this purpose. The five steps of the approach are presented below.

(1) Determination of the Heat Sources

The determination of the heat sources can be identified on the basis of the incoming and outgoing powers. This is based on the assumption that all power losses are converted into heat. For this purpose, the average of the difference of the incoming and the outgoing powers of the individual subsystems is used. If the movement is reversed, the corresponding absolute values of the powers are taken. The following Table 1 shows the power losses converted to heat sources. The losses of the power electronics are not modeled and therefore excluded in these investigations.

Table 1: Average heat sources of the individual subsystems of the EHA

Subsystem	**Heat sources**
Electric motor	47.5 W
Hydraulic pump	36.5 W
Hydraulic system	0 W
Hydraulic cylinder	0.5 W

The goal of this step is to provide an averaged heat flow so that it can be used as a boundary condition for the CHT simulation.

(2) Inserting the Boundary Conditions

The power losses that were estimated in the previous step are entered into the CHT simulation model as heat sources. The current heat losses in the copper windings of the motor are modeled as a volumetric heat source for the stator described in chapter 2.4. The heat loss of the hydraulic pump is entered at the interface between hydraulic fluid and the surrounding solid within the region of the pump. The friction between the cylinder and piston is modeled as a heat source on the inner surface of the cylinder.

The ambient temperature is chosen as the initial condition for the whole simulation domain, as well as for the fixed wall temperature of the surrounding.

(3) Running the Simulation

The simulation model is run until convergence is achieved. Besides low residuals, a thermal steady state is necessary. To check for this steady-state, several point probes on the EHAs surface were created. When the temperatures at all probes remain unchanged, convergence is achieved.

Figure 5 shows a cut view through the temperature distribution resulting from the CHT simulation model for an ambient temperature of 20 °C. Visible is the hotspot around the motor, where most of the heat enters the system. A slightly higher temperature in the region of the pump is visible. The air near the EHA gets warmer and rises due to natural convection.

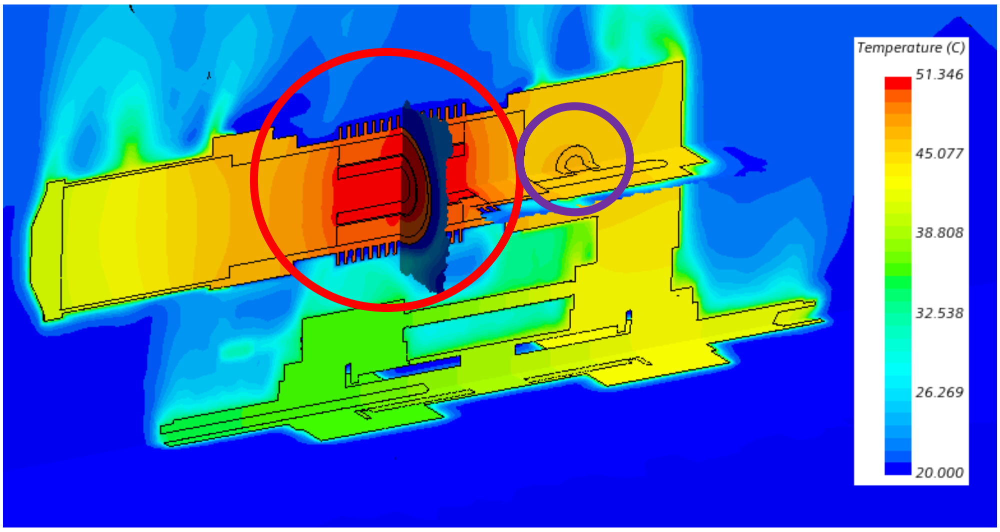

Figure 5: Cut view through the temperature distribution of the CHT simulation model for an ambient temperature of 20 °C. The Motor and the pump are encircled in red and purple respectively.

(4) Determination of the Average Temperatures

Based on the heat sources entered into the simulation domain and the different kinds of heat transfer between the EHA and the surrounding, a certain temperature field develops within the simulation domain. From this temperature field, the lumped parameters for the cross-domain simulation model can be derived.

Within the rotor and stator each, the temperature for the lumped parameter model is calculated by averaging the temperature of the volume in the respective region. The same is done for the internal hydraulic system, where the temperature for the hydraulic fluid in the cross-domain simulation model is calculated by volume averaging the temperature in the region of internal hydraulics. Table 2 shows the average temperature of the relevant components depending on the ambient temperature.

Table 2: Average temperature of the individual components depending on the ambient temperature

Component	Average temperature depending on the ambient temperature		
	-65 °C	20 °C	80 °C
Electric Motor Stator	-30.87 °C	50.23 °C	104.94 °C
Hydraulic Fluid	-35.63 °C	45.46 °C	100.16 °C

This shows how difficult it is to guess the temperature that will occur. The dependence of the load case and the ambient temperature is strong.

(5) Parametrization of the Temperature-Dependent Parameters

The temperature-dependent parameters to be considered in this case study are as follows:

- Kinematic viscosity of the hydraulic fluid
- Bulk modulus of the hydraulic fluid
- Electric resistance of the copper windings in the PMSM

There are other parameters for which the temperature dependence can be taken into account. However, these do not show a large dependency and are therefore neglected.

The temperature dependence of the kinematic viscosity can be determined using the equation according to Ubbelohde-Walther [18]. The temperature dependence of the bulk modulus can be approximated by using curve fitting.

For this purpose, the isothermal bulk modulus at different temperatures is used. Those values can be found in [19]. The electric resistance of the copper windings in the PMSM can be approximated by using curve fitting as well. The resistance for several different temperatures is given in the datasheet and can be used to extrapolate those values.

The values adjusted to the corresponding temperature are in Table 3.

Table 3: Resulting temperatures and the adjusted values of the temperature-dependent parameters

Parameter	Resulting temperatures depending on the ambient temperature					
	-65 °C		20 °C		80 °C	
Electrical resistance	-30.87 °C	0.93 Ω	50.23 °C	1.67 Ω	104.94 °C	1.85 Ω
Kinematic viscosity	-35.63 °C	274.20 mm^2/s	45.46 °C	9.20 mm^2/s	100.16 °C	3.60 mm^2/s
Bulk modulus		1.99 GPa		1.40 GPa		1.11 GPa

These parameters can now be adjusted accordingly. By running the cross-domain simulation model with these parameters, the system performance is adapted to the applied temperatures.

4. Results of the Case Study using the EHA as an Example

In the following, the described approach is evaluated. The load case is applied and compared with the different ambient temperatures. Figure 6 shows the deflection of the hydraulic cylinder plotted against time.

Due to the higher electrical resistance at high temperatures, more energy is dissipated in the system. This results in a lower deflection of the EHA at higher temperatures. This shows initially that the consideration of the temperature dependence of parameters has an influence on the system performance.

The deflection of the hydraulic cylinder decreases continuously in all cases due to the occurring losses. This is because in the applied load case the EHA does not operate with the position control (closed-loop) but with a specified rotational speed. The smallest deflection at an ambient temperature of 20°C is 45.0 mm at the beginning and is 44.73 mm after 4 further cycles. However, the crucial point here is that this influence is also temperature-dependent.

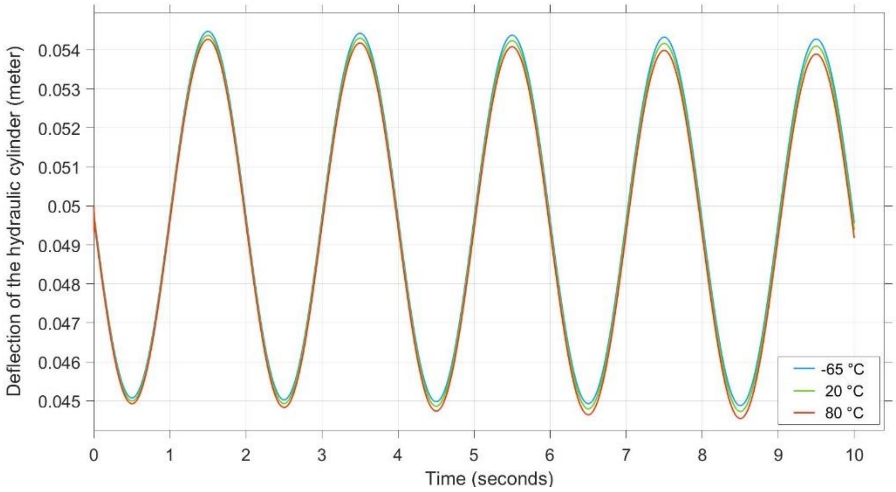

Figure 6: System performance of the EHA with different ambient temperatures

The reduction of the peak deflection for five load cycles depending on the ambient temperatures is shown in the following Table 4.

Table 4: Reduction of the peak deflections after 5 cycles due to power losses in the EHA

Ambient Temperatur	Reduction of the peak deflections after 5 cycles
-65 °C	0.2 mm
20 °C	0.27 mm
80 °C	0.38 mm

This means that there is a position difference of 0.18 mm between the two ambient temperatures -65 °C and 80 °C after just five load cycles, which are run through in 10 seconds. It is not simple to determine which temperature-dependent parameter has which influence since it is difficult to observe the influences separately. Each change has a direct influence on the power variables and therefore again on the system behavior. This study shows that the influence of the temperature is already clearly visible after a short time.

For this reason, position controllers are used for such systems. Conventional PID controllers are commonly used. To set the individual controller parameters, it is necessary to represent the system behavior sufficiently. Cross-domain models, such as those used here, can be used for this purpose. The case study shows that temperature influences the system behavior in such systems. Therefore, when considering different operating conditions at different boundary conditions, such as the ambient temperature, it is a challenge to find out the optimal controller parameters. It is especially difficult when this can only be done experimentally. A better parameterized simulation model can be used to determine the controller parameters since the relevant temperature-dependent influences are taken into account.

5. Discussion

The approach supports the parameterization of cross-domain simulations for the prediction of system performance under consideration of relevant thermal effects. It should still be carried out with validated simulation models. In addition, it must still be clarified whether this approach not only changes the system behavior but that this is also closer to reality. For this purpose, tests must be carried out on the test bench, which is then compared with the simulation concerning the system behavior, i.e. the deflection of the hydraulic cylinder. This could clarify whether this approach increases the model quality of the cross-domain simulation.

The approach can be further developed in the future. Since the power losses are also temperature-dependent, an iterative procedure is useful. In order to take these thermal interactions into account, it is necessary to adjust the parameters with each time step. Since the computing time of the CHT simulation is significantly higher than that of the cross-domain simulation, this overall simulation time would be too long. For this reason, it would be conceivable to adapt the procedure in such a way that the adjustment of the temperature does not take place at every calculation step, but only when the CHT simulation has delivered a result. In the meantime, the calculation steps of the cross-domain simulation model are carried out. Figure 7 shows the procedure of this concept.

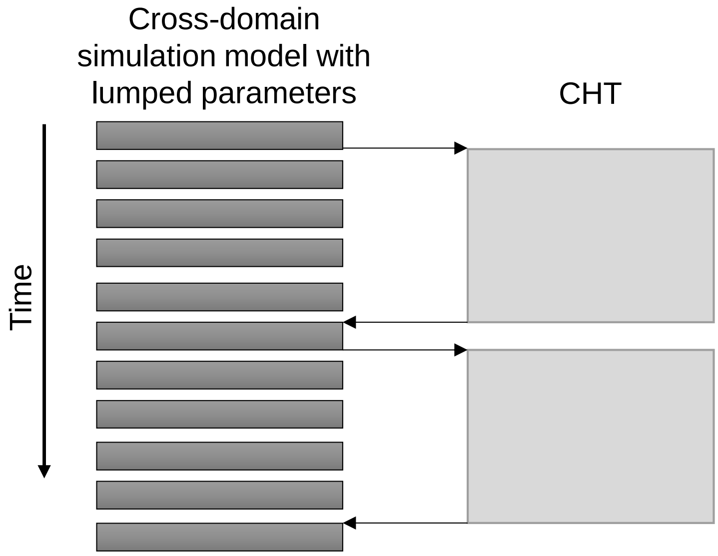

Figure 7: Iterative approach to improve the consideration of thermal interactions

The concept of the Digital Twin can be used to optimize the position controllers. For this purpose, the simulation is used for optimization and the test bench for validation [20]. The coupling of the simulation and the test bench enables new possibilities regarding the methodical solution of such problems by twinning [15]. In this context, the optimization of the control system can be done not only in terms of system performance but also in terms of energy efficiency.

6. Conclusion and Future Outlook

In this publication an approach with the combination of a basic cross-domain simulation model with lumped parameters and a CHT simulation model is described and applied using an EHA as an example. This approach is described in five steps and supports the parameterization of cross-domain simulations for the prediction of system performance under consideration of relevant thermal effects. The simulated dynamic behavior of the EHA is considered at different ambient temperatures to evaluate the approach. It was demonstrated that by using the described approach, the temperatures in the system could be estimated. The temperature-dependent parameters could be parameterized accordingly to the applied temperature. The thermal effects that affect the system behavior can therefore be taken into account.

The approach has the potential to be applied to more systems and provide better predictions of the system performance. This can reduce uncertainty in the early stages of product development and support frontloading in product development.

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