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Holistic system simulation method for the analysis and evaluation of thermal management of electrified construction machinery using inverse hydraulic modelling

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Abstract.

The electrification of construction machinery comes with new opportunities and challenges for the system architecture, leading to varying approaches and subsystem designs. Missing experiences from preceding product generations prevent an efficient comparison of system architectures early in the product development process. Thus, product development needs a tool for evaluating designs towards efficiency and energy consumption, taking functionality and environmental impacts into account. Holistic numerical system simulations enable quantitative analysis and allow comparison of concepts, without the need for tangible component designs. [1]

Electrified construction machinery is mainly described by a combination of mechanical components as well as hydraulic-, electric- and thermal circuits. A holistic system simulation describes the interaction between these domains from which two conflicting objectives arise. First, while the mechanic and hydraulic interaction is highly dynamic and takes place on short time scales, the thermal behaviour unfolds in the long-term, which leads to long periods of simulation time with high temporal resolution. Second, the complete, forward, coupling of a mechanical load simulation with the hydraulics has a high simulation complexity which comes down to extensive computational costs. [2]

As a research gap the need for an efficient holistic simulation method arises. The method shall represent all couplings relevant for the design while keeping the computational costs low, so that a quick evaluation of concepts becomes accessible. To do so, the main conflict between highly dynamic hydraulics and the long-term thermal behaviour needs to be resolved.

This contribution proposes an innovative simulation method to resolve the outlined conflict for holistic system simulations, enabling its use in the early stages of development. The main advancement is the reduction of the full bidirectional coupling of mechanics and hydraulics to a unidirectional coupling and a separation of the mechanic-hydraulic domains from the thermal simulation. The mechanics is calculated with a multibody simulation. Standard tasks and work patterns are calculated to approximate realistic forces, torques and displacements as input for the hydraulic simulation. The hydraulic simulation is implemented inversely, meaning the valve positions, pressures, and volumetric flow rates required to fulfil the mechanical movement pattern are calculated incrementally, omitting the solution of the pressure buildup equation. To comply with the required long-term analysis for thermal behaviour the output of several sequential mechanic-hydraulic work patterns is concatenated and input into the thermal simulation. This simulation method allows the efficient comparison of different system architectures and variations of subsystems and enables the initial dimensioning of the hydraulic system according to the requirements.

The usage of this holistic simulation approach is conducted exemplary on an excavator. Slewing, boom motion and driving patterns are considered providing the load and displacement input for the inverse hydraulics. The thermal simulation got the outputs of the mechanic-hydraulic simulation comprising the required electrical quantities, thermo-hydraulic losses and environmental influences to determine the required thermal regulation for the individual subsystems. This information is used to assess different designs of the cooling circuits and showcasing the added value of efficient holistic system simulations via inverse hydraulic modelling at the same time.

Keywords. electrified construction machinery, inverse kinematics, system simulation, coupled thermal-kinematic-hydraulic simulation.

1. INTRODUCTION

Electrification of construction machinery gained significant importance lately, since regulations for pollutant emissions became stricter not only for on-road vehicles but also for off-road heavy-duty vehicles. [3, pp. 780, 781] [4, pp. 1, 2] The requirements deduced from the amended regulations led to a change in the drive technology towards electric and hybrid drive concepts. These drive concepts on one hand allow to meet the requirements for pollutant emissions [5, p. 1] but furthermore offer advantages regarding noise emission, energy efficiency by utilizing recuperation of kinetic and thermal energy and optimisation of subsystem's operating point and increased productivity. [3, pp. 780, 787, 788, 797–799]

On the other hand, new challenges arise from the electrification of construction machinery. The crucial design decision is the system architecture around the electric drive system including the electronical periphery. Besides the changed drive system recuperation and electrical storage systems are required, beyond others. [3, pp. 782, 783]

One important aspect to evaluate the different system architectures is the thermal management within the machine. This includes the electrical subsystems as well as temperature control of the cabin and hydraulic subsystems. As electrified construction machines are not only a new generation of machines but involve a new drive train and energy supply concept, there is limited experience available on preceding product generations and therefore on sufficient criteria for the evaluation of the system variant's performance and optimum system design [6, p. 3]. Hence, comparing the variants of system architecture and subsystem design require analysing them during the design phase. For the evaluation of the thermal management using simulation results is feasible to reduce experimental effort and verify development considerations, furthermore, accelerating the development phase by identifying subsystems with the most potential for optimisation. To describe a system of electrified construction machinery properly, the interaction of kinematics, hydraulics and thermal behaviour within the system need to be considered in a holistic simulation approach. [7] Therefore this contribution follows the trend of coupling multiple physical domains and subsystems into a single simulation with its challenges and opportunities.[8]

2. FUNDAMENTALS

The characterization of a mechanical system with actuators, sensory and a control loop is known as a mechatronic system. As the aim of the examinations in this contribution is the thermodynamic characteristics, for evaluation the thermal management, the mechatronic system is extended to include the thermal domain, which then describes a multi physics or multi domain system. To simulate this multi physics system, each domain needs its individual modelling. Initial objective of holistic system simulations is the identification of suitable numerical tools to capture the system's characteristics. Subsequently the exchange of information and the calculation process need to be described. In the following chapter the fundamental principles for the holistic numerical approach utilized in this work to couple the afore mentioned physical domains efficiently are introduced, following the idea of assessing the thermal management for the whole system. [9]

Computational Dynamics (also referred to as multi-Body Dynamics) serves the purpose of assisting engineers during the analysis of kinematic and dynamic behaviour of complex mechanical systems comprising numerous moving bodies connected by joints. Ideally Computational Dynamics allow the prediction of the component's position, velocity and acceleration based on the external forces acting upon the individual mechanical parts. It utilises available computing power to reduce the effort for analytically/manually calculating the interaction between multiple bodies in an acceptable time. Computational Dynamics describes the mechanical domain, and its application is usually divided into rigid body and flexible body analysis, as well as kinematic determined and dynamic determined systems. While rigid body and kinematic analysis produce algebraic equations, the dynamic analysis induces second order partial differential equations to solve. The regular computational dynamics determines the accelerations, velocities and positions of the system under consideration based on the forces acting upon it. [10]

In certain cases, if the accelerations, velocities and positions for the system in question are known, it is possible to calculate the external forces in reverse. This approach is called inverse kinematic simulation. Consequently, the partial differential equations of the dynamic approach collapse to differential-algebraic equations which simplifies the solution procedure significantly. The comparison of forward and inverse simulation is depicted in Figure 2.1.

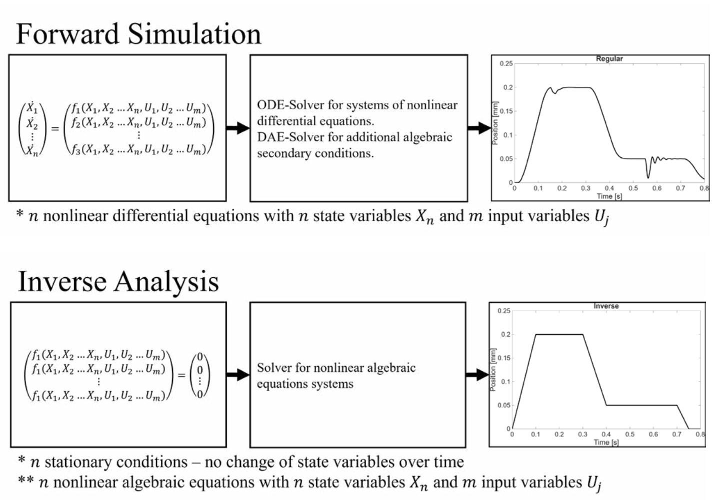


Figure 2.1: Forward Simulation a) in comparison to Inverse Analysis b) due to the inversion the equation system is simplified, while dynamic effects get eliminated from the analysis.

The approach of inverse kinematics is used frequently to analyse the forces needed to complete a functional task inside a technical system. [9,10,11,12]

Though Computational Dynamics only achieves a degree of accuracy compared to finite element calculations, which are much more accurate at a much higher computational cost, the granularity of Computational Dynamics meets the requirements for modelling complex mechanical systems. The same gradation in simulation tools is found in hydraulics, thermodynamics and electro dynamics. While for all three physical domains a continuum representation exists (i.e. CFD, CHT and CEM) the calculation with lumped parameter models, focussing on the interaction between components is used frequently for less effortful system analysis. [13,14]

Thermal simulations are primarily based on the Fourier's heat conduction equation to describe the heat flux through solid bodies. This form of heat transfer is dominating the heat development in a technical system. In addition, heat radiation and thermal convection are relevant depending on the system's physics and its boundary conditions. The main boundary conditions to be considered are the initial temperature of the system as well as its immediate environment and heat sources usually described by an input heat flux. [15, p. 265]

By reducing the hydraulic, electric and thermodynamic components to system level ordinary differential equations that describe the correlations, for example between volumetric flow rate into the cylinder and its stroke, the calculation of system dynamics is much more accessible than modelling the hydraulic cylinder using a continuous flow representation. The continuous flow representation is not only time-dependent but also a function of space and therefore leads to a complex system of computational expensive partial differential equations.

In hydraulic system simulations pressure or volumetric flow rates from fluid energy machines like pumps are specified along with control signals for the valves to analyse the hydraulic system's response comprising piston or motor accelerations, velocities and positions. In combination with control circuits that feed those positions, velocities and accelerations into a control loop modifying the input variables, specific motions of the hydraulic system are realizable.

Analogue to inverse kinematics an inverse hydraulic analysis is applicable. Instead of specifying pressure, volumetric flow rates and valve positions, the desired state of motion and position of the hydraulic system is specified, and the needed pressures, volumetric flow rates and valve positions are deduced. As with inverse kinematic inverse hydraulic reduces the computational effort at the expense of the system dynamic behaviour, which is not representable anymore.

The lumped parametric calculation approach entails an increased demand of fitting the actual system components to the, mostly generic, component substitutes of the simulation tool, while allowing longer real-world time spans to be calculated.

But, although the simulation time for each individual domain is reduced drastically, the time span in which processes happen in the individual domains differs significantly, becoming particularly notable when comparing hydraulic and thermodynamic processes. The period required in the respective physical domains for a steady state to be reached is describable by its characteristic times that originate from an analogy to electrodynamic oscillatory circuits [15]. The characteristic time is calculable from the basic differential equation of the domain regarded. The analogy between hydraulics and electrodynamics is depicted in Figure 2.2, taken from [16].

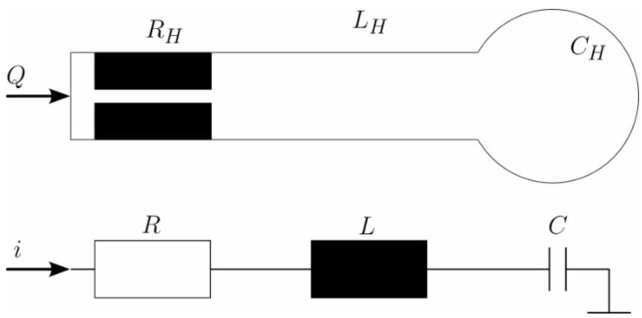


Figure 2.2: Principal illustration of the analogy between hydraulics and electrodynamics [16]

The circuit diagram can be transferred into the differential equation (1) and equation (2).

$$u = R \cdot i + L \cdot \frac{di}{dt} + \frac{1}{C} \cdot \int idt \tag{1}$$

$$\Delta p = Q \cdot R_{\mathrm{H}} + L_{\mathrm{H}} \cdot \frac{dQ}{dt} + \frac{1}{C_{\mathrm{H}}} \cdot \int Qdt \tag{2}$$

Depending on the regarded component the equations vary. By transformation to the frequency domain, characteristic time constants are derived which indicate required period for a change in state of the component described. The analogies between electrodynamics circuits and the relevant domains for the analysis in this contribution are listed in Table 2.1.

Table 2.1: Electrodynamic Network Analogy for Hydraulics, Thermodynamics and Mechanical Systems

				Characteristic Times
Electrodynamics	Capacitor C	Inductor I	Resistor R	$\tau = RC, \frac{L}{R}, \sqrt{LC}$
Hydraulics	Hydraulic Capacitor $C_{\mathrm{H}} = \frac{V_0}{K_{\mathrm{Fl}}} = V_0\beta$	Hydraulic inertia $L_{\mathrm{H}} = l \cdot \frac{\rho}{A}$	Cylindrical pipe (Hagen-Poiseuille) $R_{\mathrm{H}} = \frac{12 \cdot \eta \cdot l}{\pi \cdot r^4}$	$\tau = RC, \frac{L}{R}, \sqrt{LC}$
Thermodynamics	Heat Capacity $C_{\mathrm{TH}} = C_{\mathrm{p}}, C_{\mathrm{v}} \left[\frac{\mathrm{J}}{\mathrm{K}}\right]$	-	Thermal Resistance $R_{\mathrm{TH}} = \lambda \cdot l \left[\frac{\mathrm{K}}{\mathrm{W}}\right]$	$\tau = \lambda \cdot l \cdot C_{\mathrm{p}}$
Mechanics	Spring $C_{\mathrm{m}} = k$	Inertia $L_{\mathrm{h}} = m$	Friction $R_{\mathrm{m}} = D$	$\tau = \sqrt{\frac{m}{c}}$

From this analogy the different characteristic times for the lumped parameter systems are calculable, which allows an estimation of the overall simulation time needed. A hydraulic network, typically consisting of valves, pistons and tanks, reaches its stationary state in the order of seconds. To capture the hydraulics dynamic behaviour, simulation time step sizes below $< 1 \cdot 10^{-3}$ [s] are necessary. Based on experience a thermodynamic system reaches a stationary state in the order of minutes or hours, depending on its size, which leads to time step sizes bigger than 1 [s] to capture the systems dynamics. In many cases in Multiphysics, a problem emerges, if those domains are considered in combination within a single simulation approach, since this forces the calculation of thermodynamic effects on a hydrodynamic timescale if no measures are taken. A combined hydraulic and thermal simulation ultimately leads to a significant overhead in computational costs, which is why an innovative approach is needed to bring those two domains together.

3. RESEARCH OBJECTIVE AND APPROACH

The evaluation of newly developed electrified construction machinery and its subsystems, accordingly, regarding the thermal management is sensibly conducted using simulation tools for the system description. The relevant subsystems include mechanical kinematics, hydraulics and thermal processes, which raises the obstacle of conflicting time scales between the hydro-kinematic and the thermal characteristics of the system as derived in chapter 2. While the characteristic of hydraulic and kinematic subsystem is highly dynamic, the thermal behaviour is long-term in comparison. A holistic simulation of these domains, reconciling the significantly different time scales, requires innovative simulation methods, which outlines the research gap.

The objective of this contribution is to introduce a holistic simulation methodology, that enables coupling kinematics, hydraulics and thermodynamics while concurrently reducing simulation time and effort to a minimum.

The proposed solution provides for a reduction of the coupling between mechanic-hydraulic and thermal behaviour from bidirectional to unidirectional. This allows the simulations to be separated.

The mechanical part of the simulation is modelled as a multi body system, depicting the bodies' kinematics. Kinematics and hydraulics both are simulated inversely and unidirectionally coupled using the inverse kinematics' output as the inverse hydraulics' input. The hydraulics output combines the results of the hydraulic-mechanical coupling and is input of a subsequent forward thermodynamic simulation. To match the longer time span of thermodynamic phenomena the short-term hydro-mechanical simulation output is concatenated over time. [12]

Using this simulation methodology highly dynamic phenomena, mainly settling-in behaviour, in hydraulics are omitted to make the simulation less CPU-intensive. Furthermore, the hydro-mechanical simulation must be calculated only once, instead of repeatedly over the whole period the thermal behaviour takes up. Thereby, the thermal simulation becomes substantially more efficient and less effortful.

4. SIMULATION METHODOLOGY

The simulation methodology for modelling electrified construction machinery and similar applications according to thermal behaviour taking electric and hydraulic losses and external thermal influences like thermal radiation into account, bases on the idea of a holistic and simultaneously efficient simulation. The approach for a holistic model needs to handle the time scale difference between mechanical and hydraulic phenomena and thermal phenomena. This challenge is addressed by subdividing the simulation according to the time scale. The hydraulic-mechanical simulation is separated from the thermal simulation by decoupling the two simulations in one direction, so that the unidirectional coupling from the hydraulic-mechanical part to the thermal simulation remains.

The desire for efficiency furthermore demands low effort simulation methods for both, the highly dynamic mechanical and hydraulic part and the long-term thermal behaviour. For this reason, the mechanical and the hydraulic simulation are unidirectionally coupled, as well. This way it is possible to implement inverse simulations to the mechanics as well as the hydraulics. In comparison, the conventional forward simulation uses the input of manipulated variables e.g. force in mechanics or valve positions in hydraulics and simulates the causal system behaviour, outputting dependent variables like movements or pressure build-up, principally depicted in Figure 2.1 a). Whereas the inverse simulation illustrated in Figure 2.1 b) predefines the dependent variables, e.g. a position of components in a mechanical system and calculates backwards to determine the input variables' values required to achieve the predefined dependent variables. The inverse simulation is advantageous regarding computational effort and thus simulation time due to the omission of transient phenomena, especially oscillations, which moreover reduces the partial differential equation system to a nonlinear ordinary differential equation system.

Mechanical Simulation

The overall simulation methodology is presented in Figure 4.2. As described the mechanical simulation is implemented inversely as a multi body system (MBS) simulation, that is generally able to provide approximately realistic forces, torques and displacements for standard tasks and work patterns of systems. The inverse mechanical simulation is reduced to a mere kinematic simulation, excluding the transient effects considered in a forward simulation, as mentioned in chapter 2. The highly dynamic transient effects are computationally expensive but their impact on the thermal behaviour of the system is insignificant, allowing for them to be neglected in a thermal analysis.

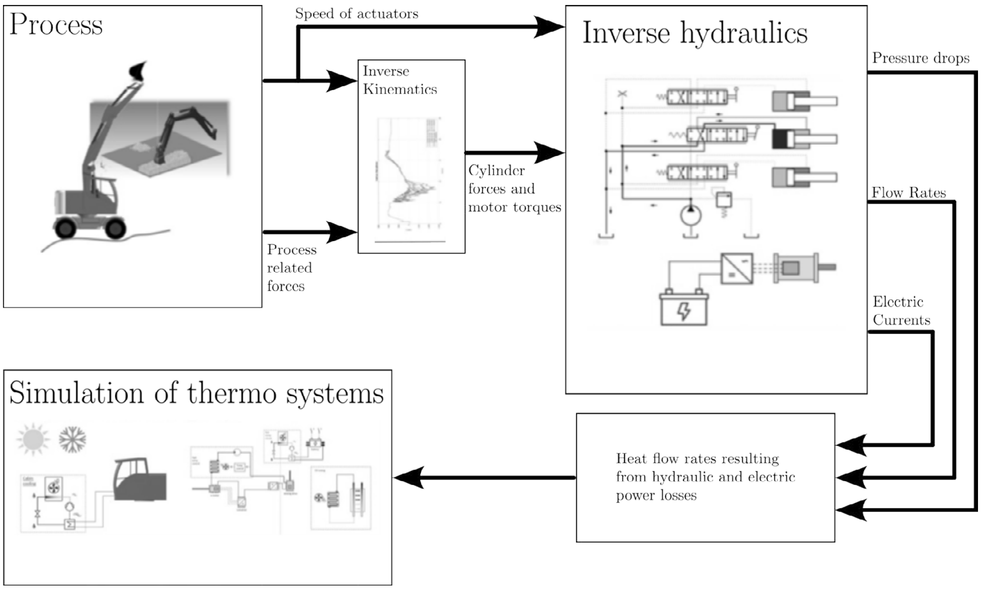


Figure 4.1: Overview of the simulation methodology.

For the inverse kinematic simulation of construction machinery, first the movements of all relevant components of the machine are defined, determining the free degrees of freedom (DoF) and considering restrictions of the component’s connections in form of bearings and joints. This results in internal and external forces and torques. The external forces and torques arise from gravity and the interaction of the construction machine with the environment and are forwarded into the system where they cause internal forces and torques in the joints. The joints comprise bearings, swivel and thrust joints as well as the hydraulic cylinders also considered as thrust joints. In the unconstrained DoFs of the bearings and conventional joints, the movements are simply performed, since there is no counterforce or torque, while the forces and torques in the constrained DoFs are supported by the bearings. The hydraulic cylinders experience forces along the direction of piston movement since they can apply a counterforce. This counterforce is determined by the inverse kinematic simulation for each cylinder and describes the required actuator force to achieve the predefined movement and displacements, respectively. The determined cylinder forces subsequently serve as input for the hydraulic simulation. Compared to complex inverse kinematic problems like robotics, where iterative methods are necessary to reach a solution with inverse kinematics since a multivariant problem is looked at, the motion of an excavator or similar piece of equipment is quite simple with a small solution space. Therefore, the inverse kinematic solution is simpler and therefore more accurate. [17]

Hydraulic Simulation

The hydraulic subsystem is modelled using mechatronic system simulations with specified hydraulic and mechatronic components, e.g. cylinders with given Pivot-point. Like for the mechanic simulation inverse hydraulic simulation is used to exclude highly dynamic effects of a real hydraulic control system that are likewise neglectable for the overall result of the thermal system behaviour.

The inverse hydraulic simulation resorts to the inversely calculated required forces from the kinematic simulation. The inverse hydraulic uses the equation system, equivalent to the equation system in Figure 2.1 b) to calculate the required pressures and therefore volume flows in the cylinders, parameterised by their cross section and stroke, and valve positions as well as electric control signals for the system control for providing the desired actuator forces in the mechanical system.

The perfused valves, the piston movements and the electric currents for the control signals are subject to thermal losses. These losses represent the relevant thermal influence of the hydraulic subsystem on the overall machine and is consequently input to the thermal simulation. The simulated period is short, though, compared to the time span of thermal phenomena. And while the other thermal influences are nearly stationary the thermal influence of the mechanic and hydraulic system varies during operating of the construction machine and depending on the operating condition. To depict an average of the operating conditions, weighed with their assumed average duration, it is recommended to generate and simulate operation cycles in the mechanical and hydraulic subsystems. The determined thermal losses during the operation cycle are concatenated over time and used for the thermal simulation. The repeated operation cycles, provide a realistic approximation of the system's thermal behaviour in a real application, while in contrast a single operation only provides information about the thermal impact of this operation and neglects relevant further influences. The estimation is feasible for the initial system design and component dimensioning required to fulfil the requirements in terms of temperature management of the overall system.

Thermal Simulation

The thermal simulation is conducted conventionally forward. The concatenated heat input from the mechatronic and hydraulic simulation, arising from electric losses in motors, the inner resistance of the battery, inverters and hydraulic losses due to drops in pressure within the valves, transient losses in the compressor and exhaust heat in the converter are used as an input modelled either using the efficiency factor or if available characteristic curves. Furthermore, external heat sources like the environmental temperature and solar radiation on the cabin of the machine and internal heat sources like the air conditioning including the cooling cycle. The heat flux in between the subsystems and domains is calculated using dedicated connector elements describing the thermal transfer behaviour based on the fundamental thermodynamic equations as described in chapter 2 and local temperatures. The temperature changes and heat flux are provided as a result. From these outputs information about the temperature control or the overall thermal energy loss can be deduced. Further examples of potential interpreted results are presented in the following chapter, where the methodology is exemplary applied to an excavator.

5. Exemplary Application by Means of an Electrified Excavator

To demonstrate its operating principle and benefits the presented methodology is applied to a case study. The electrified excavator presented in the following is a generic design without a real-world equivalent but provides a level of detail close to a real-world system. For the mechanical domain the drivetrain and sewing drive as well as the excavator arm are modelled as multibody systems. The individual hydraulic cylinders for the excavator arm are supplied by a hydraulic circuit, depicted in Figure 5.2. The drivetrain, sewing drive, oil pump and coolant pumps are all driven by alternating current electric motors, which are supplied from power electronics, converting the direct current from the battery block to appropriate alternating currents for the electric motors. The multiple thermal circuits in the model compensate for the efficiency losses caused by transformation losses or friction, which produces heat. The oil of the hydraulic circuit is passed through a heat exchanger, modelled as a single fluid circuit giving off heat to a thermal mass, to compensate for the hydraulic losses. A low temperature coolant circuit is modelled for cooling the power electronics and the electric drives operating the pumps and drivetrain, comprising two cooling circuits with liquid ethylene glycol in one and coolant R134A in the other circuit, exchanging heat via contact to a chiller. Another coolant circuit with exchange of heat between fluid circuit and coolant circuit is deployed to regulate the battery system. Contrary to the oil cooling the coolant circuits for the power electronics and battery are temperature controlled since the electric components are only operable close to standard conditions. Finally, cabin air conditioning is included in the thermal domain analysis, which ultimately represents a temperature control giving off heat to a thermal mass, too. Separating the different cooling circuits allows to individually regulate each temperature in the most efficient working point of the component or subsystem. Aside from the cooling circuits heat radiation from the cabin towards the environment is considered as a heat sink as a counterpart to the solar radiation into the cabin.

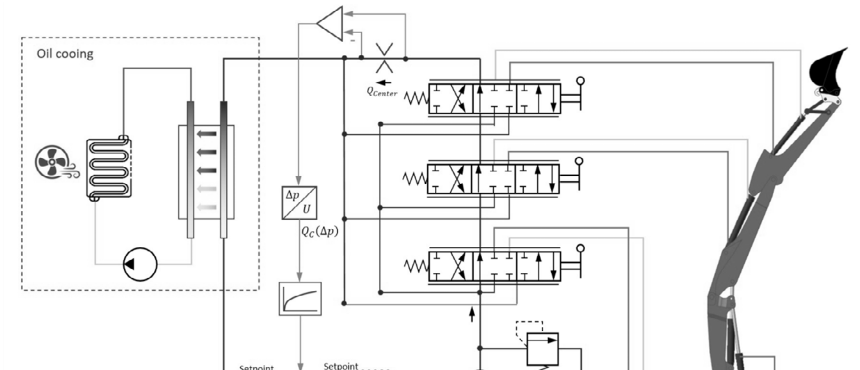


Figure 5.1: Schematic hydraulic circuit diagram of the excavator arm

In total the model consists of a mechanical, electrical, thermal and hydraulic dimension with, multiple, partly independent, circuits. A schematic overview of the system, including mechanical, hydraulic and thermal coupling of the excavator arm, is given in Figure 5.1.

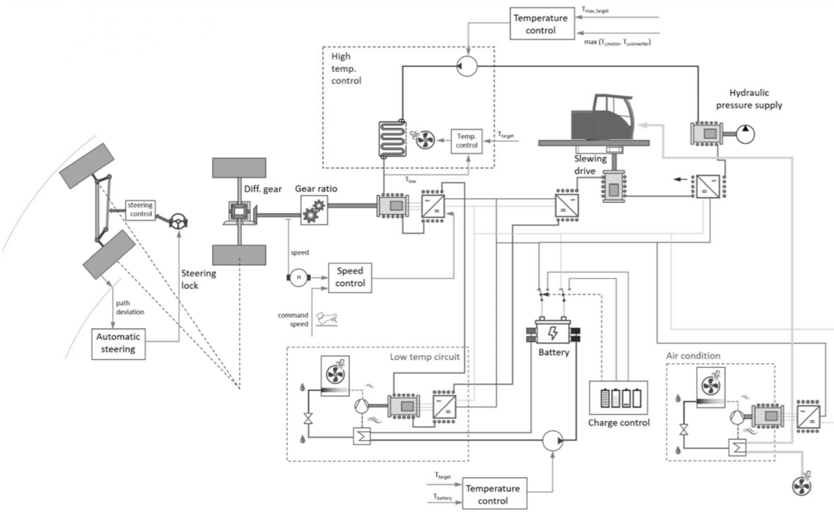


Figure 5.2: Electric actuators and cooling circuits of the exemplary excavator arm

To conduct a holistic system simulation and analyse the thermal management, which was implemented as described, a load cycle and environmental conditions are needed. The load cycle needs to represent realistic work pattern for the construction machine including slewing, drive patterns and boom motion. For the simulation the following work cycle is assumed:

- 5x Moving earth – based on a particle Simulation
- 1x acceleration/deceleration
- 1x uphill and downhill drive
- 1x idle slewing
- 1x idle boom motion

A single duty cycle takes four minutes and is looped 10 times for a single simulation to reach stationary conditions for each physical domain, which leads to a depicted real time of 40 minutes.

Figure 5.3 shows the drivetrain torque for the working cycle compared to the temperature development in the cooling circuit of the power electronics in Figure 5.4. The plots show how the thermal domain develops over multiple cycles while the drivetrain reaches its stationary states immediately. These results are consistent with the known discrepancy in the timescale between long-term thermal phenomena and considerably shorter-term mechanical, electrical and hydraulic phenomena. It also highlights the need to concatenate load cycles multiple times to obtain reliable information about the system behaviour.

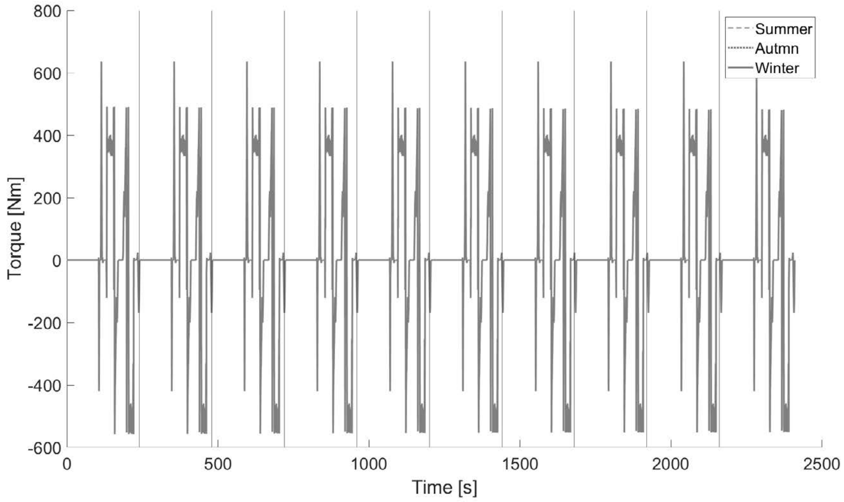


Figure 5.3: Torque progression over time of the drivetrain

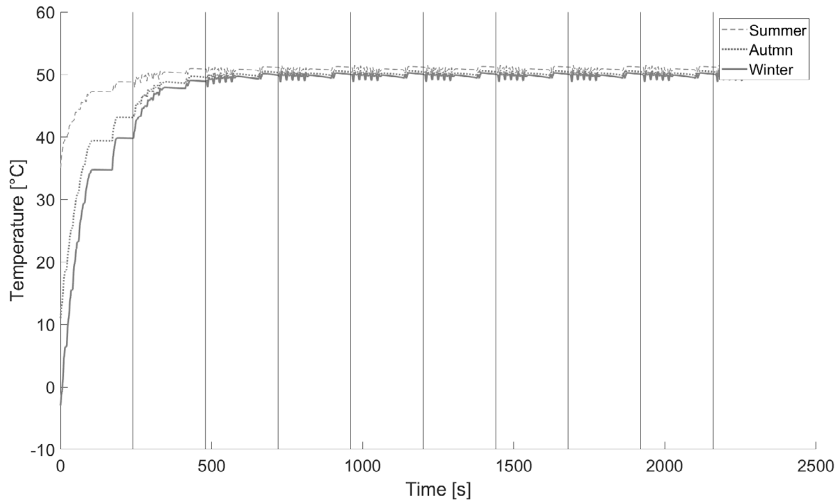
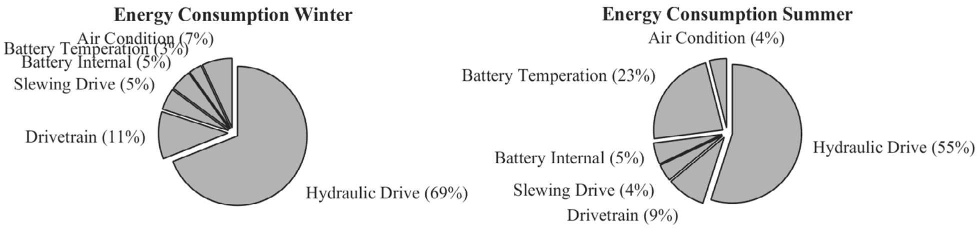


Figure 5.4: Temperature development over time of the power electronics coolant

Figure 5.4 also contains multiple plots for different environmental conditions that are tested to identify the dependency of the thermal management system on the environment. Therefore different, central European, seasons were taken as a basis:

- Summer: Temperature: 35 °C; Humidity: 78 %
- Autumn: Temperature: 11 °C; Humidity: 98 %
- Winter: Temperature: -3 °C; Humidity: 85 %

This analysis for different environmental conditions allows the evaluation of the relative energy consumption of the tested design. Figure 5.5 shows a comparison between summer and winter according to the proportional energy consumptions arising after the system reached its stationary thermal operating conditions.



These evaluations are only possible because the system is considered holistically. It allows, aside from analysis of the total energy consumption, to identify design areas that are most promising for improvement. Furthermore, this example already emphasizes the cruciality of the environmental conditions for the design of thermal management systems. The battery cooling system for example has a significantly higher impact in the summer than the winter, compared to the other considered subsystems in this study. An analysis that ignores these differences could lead to flawed design.

6. DISCUSSION

The proposed simulation methodology serves as an analysis tool during the system development phase with the aim to enable a quantified evaluation and comparison of system concepts regarding the thermal aspects. Prerequisite for the use of the simulation methodology is, as with simulations in general, a sufficient level of details of the design to have the necessary information for a calculation available. This allows the methodology's application during the late concept and draft phase of the product development process. In this phase the simulation following the presented methodology allows a data-based comparison of different system architectures and an initial dimensioning of the components. Besides information about interrelations within the system and the impact of present influencing factors become known and understandable.

The simulation methodology omits the transient and highly dynamic processes of the mechanical and the hydraulic subsystem, as their impact on the long-term thermal development within the system is insignificant and therefore feasible to neglect. Furthermore, transient effects like friction and leakage are only represented to a limited extend by efficiency factors. These simplifications lead to a limited accuracy of the resulting values but still provides useful information about the main interrelations within the system and the main influencing factors as well as an estimation of the required subsystem and component dimensions. Another limitation of the inverse kinematics is that the exact and physically possible moving path of the components is not calculated. This is acceptable for the initial concept simulation because the exact moving path' do not influence the results for the forces substantially. For cases that require a detailed analysis of these effects as well as for the further steps of the product development process, an adaption of the methodology is recommended, resorting to transient forward simulations. As this approach revokes the decisive advantage of reduces computational and time effort, it is only sensible during later development phases or in separate simulations.

7. Conclusion and Outlook

Electrified construction machinery offers a variety of advantages, especially the compliance with the latest emission regulations. Using the simplifications of inverse kinematics and hydraulics, as well as the unidirectional coupling of mechanics to hydraulics and hydraulics to thermodynamics, the presented methodology enables a holistic and efficient simulation and evaluation of the thermal properties of a mechanic-hydraulic system, particularly designated for electrified construction machinery. This methodology allows for system understanding, system concept comparison and initial dimensioning during the early product development phases.

The example of the excavator demonstrates the applicability of the proposed simulation methodology on an academically level and provides the prospect on an application in a real system. As an outlook the verification of the methodology by a comparison to a fully coupled simulation and measurement data of a real example of an excavator are of interest to examine the accuracy of the simulation. To furthermore validate the application and the advantages of the simulation methodology the application in a practical development process is pending.

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