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Analysis of dynamic system behaviour using sequence modelling with the C&C²-Approach – a case study on a power tool hammer mechanism

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Abstract (300-500 words)

In product development, the building of simulation models for analysis is a general approach. Nowadays, products are mostly developed in generations, which means these models can be re-used in subsequent product development projects. This intensifies the use of complex models. An issue for using these complex models successfully is that the causes for dynamic system behaviour are sometimes unknown, which makes parametrisation of the model difficult. The relevance of parameters for this system behaviour are difficult to investigate and often have to be assumed. In this case the achievable knowledge with the created simulation model is limited, which can hinder successful product development.

This paper shows how a structured system analysis can support the parameterisation of complex, dynamic multi-domain models. In the described case, the hammer mechanism of an impact wrench is investigated using this approach. The dynamic system behaviour during fastening of a screw is analysed and modelled using the C&C²-Approach. This approach can be seen as a thinking tool that helps in investigation of relations of parameters of the systems embodiment to the systems behaviour. With this approach, models of these relations are built up as basis for the simulation model. In this analysis and model building of the impact wrench, the systems behaviour is differentiated into states that are defined through qualitative changes in the systems embodiment. Then a simulation model is derived to quantify these relations. This model is parametrised following the defined states. During verification of the built up simulation model of the impact wrench, an unexpected system behaviour is discovered and investigated. The investigation leads to findings of new states, as the systems embodiment behaves different from what was expected in one state. This behaviour was not identified before as this part of the system is difficult to observe. The C&C²-Model was extended through integration of the new states. As the simulation model was derived from the C&C²-Model, its improvement was possible in a lean way. The improved simulation model shows the new states and extends the understanding of the system behaviour of the impact wrench.

Keywords: Modelling, validation, product development, power tools, case study

1 Introduction

In product development, the final product is developed with support of virtual models such as CAD-models, FE-simulation models or physical models like prototypes. Models in general represent a simplified aspect of reality with focus towards their purpose for the model builder (Stachowiak, 1973). The key to successful usage of models is simplification without losing relevant information. In product development, the modelling of dynamic behaviour of a product or its subsystems is often necessary to understand and then optimise the product. Recent products are often very complex, therefore it takes much effort in time and cost to derive a model, which can simulate their dynamic behaviour. However, this is often worth the effort, as most products are developed in generations and knowledge can be re-used. This intensifies the use of complex models. Non-proprietary, object-oriented, equation based languages like Simscape™ or Modelica® are commonly used to conveniently model complex physical systems throughout various domains. These simulation models need defined relations of parameters of the systems embodiment and its behaviour. Product developers can use former simulation models, experimental data and documentations of the design process as basis to build such a model. However, many assumptions, especially about the relevance of parameters have to be made implicitly. The causes for certain system behaviour remain sometimes unknown, when assumptions do not correspond with reality.

The problem is that unknown causes for (unwanted) dynamic system behaviour can obstruct the product development. The research question derived from this problem and addressed in this paper is:

How can relevant relations of dynamic system behaviour and parameters of the embodiment be identified, described and verified in a structured approach?

This question will be investigated at the example of an impact wrench.

2 Materials and Methods

To answer the research question, a case study on the dynamic behaviour of an impact wrench is conducted. Impact wrenches are used when high torque is demanded in applications that require handheld power tools, for example in steel construction or repair shops. The big advantage of impact wrenches is the low exertion of the user while applying high torque on bolting applications. This is done by using a rotational hammer mechanism, where the hammers moment of inertia supplies the energy for the torque development. For applications where bolts are loosened, the impact wrench is commonly used because of its advantages in speed and user exertion. In applications where tightening of bolts is necessary there are issues regarding the precision of the resulting clamping force. The torque of an impact wrench arises dynamically and therefore strongly depends on the interactions with the system environment. This means that different screw connections and also different use cases or users greatly influence the resulting force. Even in the process of tightening a bolt, with increasing the preload in the bolted connection the effective stiffness rises and the amplitude of the impact torque rises, too (Sieling, 1977). Formulas and tables which show the interrelationships are difficult, therefore impact wrenches are not allowed to be used in most applications or are provided with a high safety factor like in the VDI 2230 (VDI, 2015). Deeper investigation of the impact wrench is elaborate, as power tools are difficult to investigate using current test benches, as Matthiesen et al. (2017) have shown at the example of an angle grinder. The conducted case study was done by creating a simulation model of an impact wrench using a structured approach to identify relevant parameters for its system behaviour. Aim was to increase the understanding of the dynamic behaviour of the impact wrench as basis for further development to extend its field of application.

2.1 Materials: The impact wrench

The basis of the functions of an impact wrench is the hammer anvil principle. The hammer is accelerated by an external, mostly continuous torque and serves as a storage of kinetic energy. The tangent collision of hammer and anvil creates the torque. During the impact, a portion of the energy stored in the hammer is transferred to the anvil. The time in which the energy is transferred is shorter that the acceleration phase of the hammer. Therefore, the magnitude of the impact is much higher than the magnitude of the external torque source accelerating the hammer. This principle is implemented in impact mechanism of impact wrenches. The impact wrench consists of a multitude of components around hammer and anvil that are shown in Figure 1.

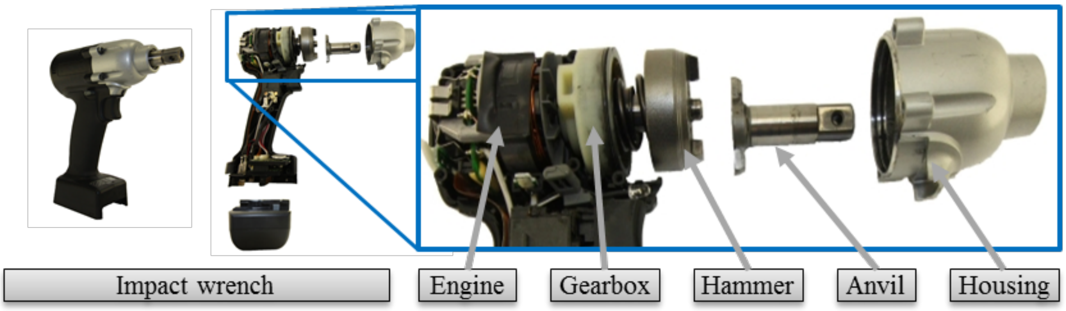

Figure 1: Subsystems in the impact wrench

The drive shaft has two opposing v-shaped grooves with a semi-circular cross-section on the outer surface, in which two steel balls are located. The hammer, which also has two mirrored internal V-shaped groove tracks manufactured on the inside, is mounted on the drive shaft and connected with it by the two steel balls. The interaction of hammer and drive shaft is shown in Figure 2. The rotation of the hammer is coupled with the axial movement of the hammer with respect to the drive shaft by the balls following the grooves on both parts.

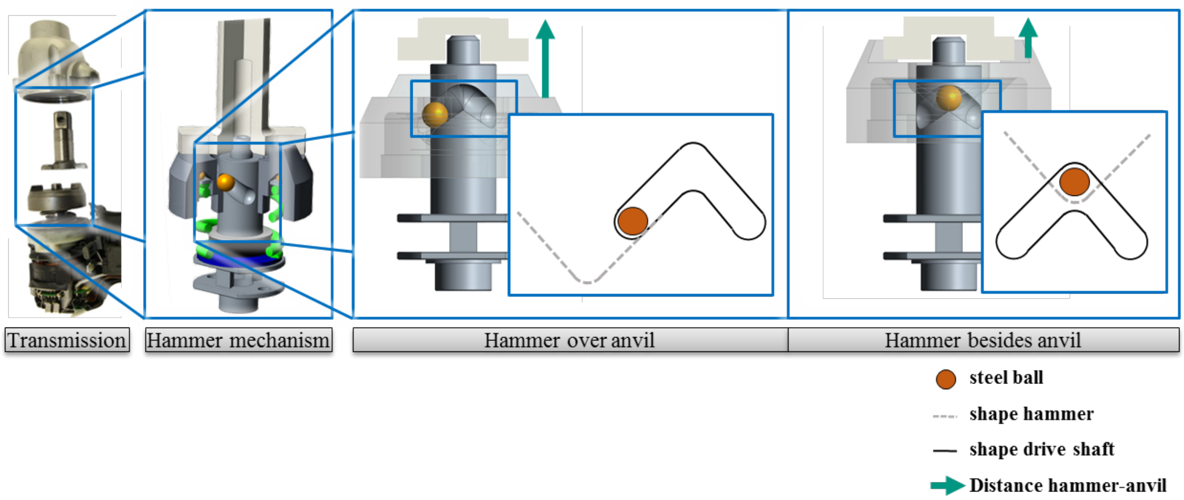

Figure 2: V-shaped tracks of the hammer mechanism

2.2 Methods: structured modelling of states and sequences

To gain knowledge about a systems parameters and their relation to the dynamic behaviour, the differentiation of its behaviour into states can be used. Methods for modelling of states are mostly focused on software development, for example the entity relationship model (Chen, 1976) or the statecharts (Harel, 1987). These modelling methods help to depict and structure a system, however in analysis questions of product development their support is limited as they don't include elements to analyse and identify function-relevant parameters of a systems embodiment. In product development, approaches like Axiomatic Design (Suh, 1998) or the FBS (Gero & Kannengiesser, 2004) are used to describe design processes and contain elements to describe the characteristic entities and relations. They focus on understanding and modelling of design processes, therefore their potential in analysis of relevant system parameters is limited. The CPM (Characteristics Properties Model) comprises elements to describe characteristics and properties of a product (Weber, 2005). It focuses on structuring of these elements to support product developers in handling them in complex products. In problem solving tasks, visualisation can be supportive (Stylianou, 2002). In product development, the domain theory (Andreasen, Hansen, & Cash, 2015) contains aspects for explicit modelling of parts and their relation to functions in the "organ domain" and describes models to do so. These models often use visualisation and symbols to describe the relations, This principle of visualisation to solve problems in product development is used in the C&C²-Approach (Matthiesen, 2002), (Albers & Wintergerst, 2014) to model relations of function and embodiment through symbolic elements. It was developed to support product developers as a thinking tool for modelling relations of embodiment parameters and system behaviour. It enables the structuring of thoughts about these relations through its elements. It is used to express ideas, assumptions and insights in explicit visual models (see Figure 3). Handling relations of embodiment and system behaviour is important for design engineers, as they need to pre-think and document an embodiment of a technical system to enable its functions (Matthiesen, 2011). The C&C²-Approach will be used in this study as it is fit best for a structured approach that is addressed in the research question. It will be explained in more detail.

In its application, the C&C²-Approach needs a modelling purpose as basis. From that, the boundaries of the investigated system are set to focus the analysis. Boundaries of the system can be of area, where only parts of the system are investigated, or of state, where a specific period of time during function fulfilment is investigated. In the set boundaries, visualisations of the systems embodiment are derived, which show their relations to the behaviour. See also Figure 3, middle. These visualisations can be for example a sketch of the system, a CAD-cross section or a photo of a real system. It is important that relevant embodiment for the investigated system behaviour is visible to enable the expression of thoughts about their relations. The key elements of the C&C²-Approach are then used to create a representation of the relations between embodiment and the systems behaviour. The key elements are the Working Surface Pair (WSP), the Channel and Support Structure (CSS) (Matthiesen, 2002) and the Connector (C). The WSP is created when two arbitrary surfaces get in contact and become part of transmission of energy, material or information. The CSS connects two WSPs and transmits energy, material or information. The C comprises the effects of system parts outside the modelled system. It sets the system boundary of area for the C&C²-Model. These elements are shown in Figure 3 (left side). The initial C&C²-Model is completed by assigning parameters to the key elements. More detailed models can be derived if necessary or the system boundaries can be shifted to investigate other parts of the system using this initial C&C²-Model.

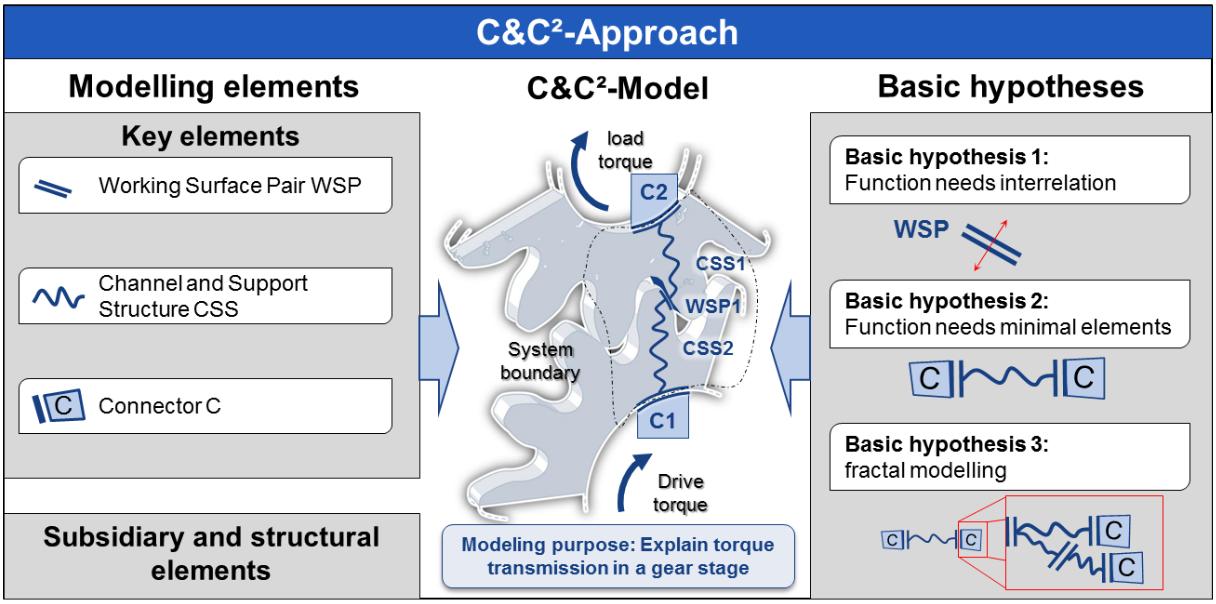

Figure 3: The C&C²-Approach, according to (Matthiesen et al., 2018)

When a system changes its state, the C&C²-Model changes as well, as WSPs, CSSs or Connectors emerge, disband or change their properties. These C&C²-Models can be connected and then form a C&C²-Sequence model (Albers, Matthiesen, Meboldt, Alink, & Thau, 2008), (Matthiesen & Ruckpaul, 2012). An example of a C&C²-Sequence model is shown in Figure 4. There are two states displayed and the emerged WSP A1 (red) defines the change from state 1 to state 2.

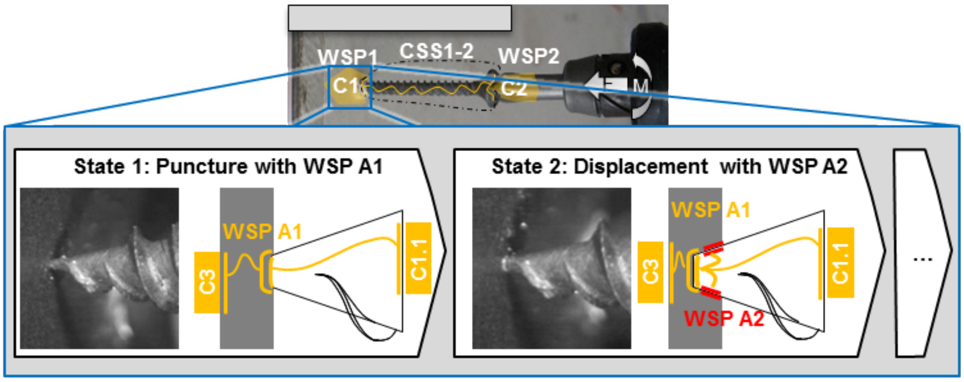

Figure 4: C&C²-Sequence model at the example of a self-drilling screw (Matthiesen et al., 2018)

In this study, a simulation model based on the relations modelled in the C&C²-Sequence model of the impact wrench is derived in Simscape™. By using this simulation model, the relations of embodiment and system behaviour can be quantified. For example, the C&C²-Sequence model shows that the hammer hits the anvil in a certain state and transmits torque, but the torque height remains unknown (see also Figure 8). The knowledge of the value of the torque is important for designing of the contact area of hammer and anvil and can be achieved using the simulation model.

The result of the simulation determines a quantitative embodiment function relation, which expands the qualitative model understanding described in the C&C²-Sequence model. Sometimes the cause for observed behaviour is unclear in a qualitative or quantitative way. This is called an observation barrier, where the relevance of design parameters towards system behaviour remains unknown. Identification of these parameters is often necessary to improve a product. To do so, analysis methods are used. A structured approach to choose a fit analysis method for resolving an observation barrier is the analyseKIT, that provides methods according to the type of the observation barrier (Matthiesen, Hoelz, & Grauberger, 2017).

3 Results

At the beginning of the analysis, an initial understanding of the relations of the embodiment and system behaviour of the impact wrench is needed as basis for the modelling of the dynamic system. An initial static analysis of the components with the C&C²-Approach is conducted. A resulting C&C²-Model of this analysis is shown in Figure 5. It shows the interaction of hammer and anvil in the hammer mechanism of the impact wrench. On this basis, the temporal change of the system is modelled.

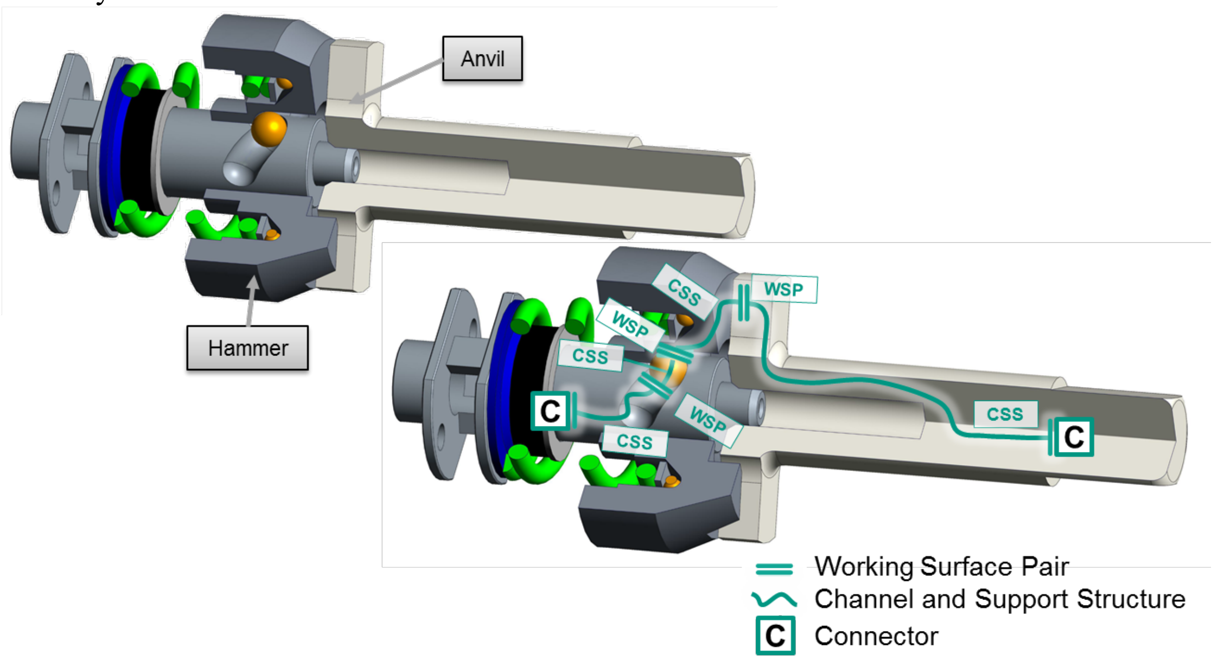

Figure 5: C&C²-Model of the hammer mechanism of the impact wrench

On the overall system observation level, two operational states for the described impact mechanism are differentiated. The system is in the first state when the demanded output torque is below a threshold. In this state, torque is transmitted at a nearly constant angular speed. In bolting application this state is called 'run down'. The system switches into the second operational state when the threshold is reached and the hammer mechanism is activated. While in this state, it can be divided up into six sequential states. These states are investigated further, as dynamic behaviour becomes relevant when the hammer mechanism is active. These states are shown in Figure 6.

The first state is called spring relaxation. The hammer accelerates in positive angular direction due to the decompression of the previously compressed spring. The second state is reached when the acceleration of the hammer is finished. In this state the hammer rotates with approximately constant speed. This state ends with the creation of the tangential working surface pair between hammer and anvil. The initiated state is referred to as the impact, in which the resulting tangential interaction between hammer and anvil creates the output torque, with an impulse characteristic. The amplitude and duration of the impact torque depends on many parameters like the moment of inertia, the angular speed and system stiffness.

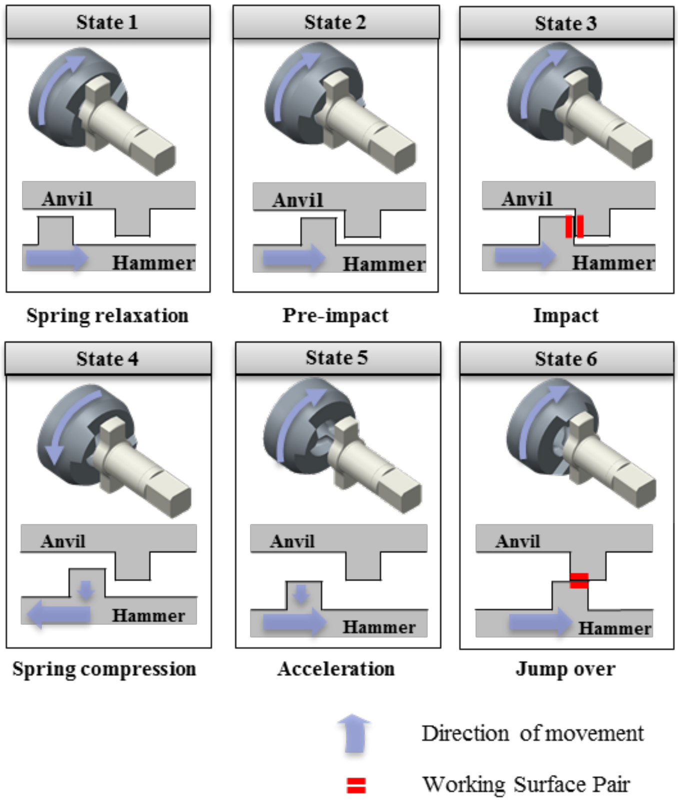

Figure 6: states of the impact wrench from the simulation

The fourth state starts with disbanding of the working surface pair between hammer and anvil. The recoil reverses the angular hammer speed, which causes the axial movement of the hammer and spring compression due to the interaction between the working surface pairs of the ball-contact. In the fifth state, the hammer is accelerated again, while the spring is still compressed and therefore the hammer is also axially displaced. The following sixth state is called 'jump over', because due to the axial displacement of the hammer the teeth of the hammer over jump the anvil. With the end of this state the spring starts to decompress and the sequence then starts again with the first state. Since the anvil and hammer each have two 180° offset striking surfaces, the sequence is repeated twice every 360° mechanical rotation of the drive shaft with fixed anvil. The changes of the states are visualised through blue arrows that show the moving direction of the hammer. The change from state 1 to state 2 is defined through acceleration, as the hammer gathers speed in state 1 and moves at almost constant speed in state 2.
Based on this model understanding, the simulation model was derived. Parameters of the system components, such as inertia and stiffness, were calculated using CAD and FEM software. Additionally some parameter values where achieved through experiments. The whole model was build up in Simscape™ following the states defined in the C&C²-Sequence model.
In the verification of this simulation model through measurement of the preload force of a screw connection that was fastened with the impact wrench, the real system behaviour differed from the simulation model output. Figure 7 shows a second force peak in the data.

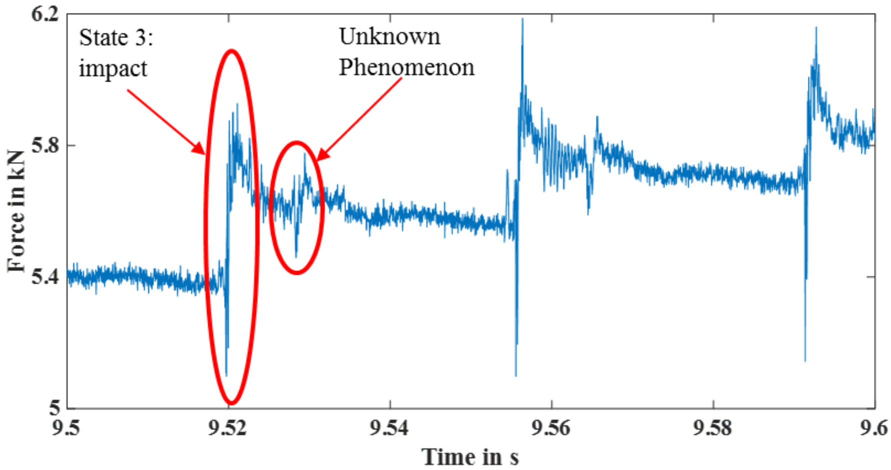

Figure 7: Phenomenon in the preload force of a screw connection fastened by the impact wrench

It is unclear, whether this is a real behaviour of the impact wrench, or an effect from the environment or measurement. This observation barrier is resolved with the analysis method "show me, don't tell me", where the behaviour of the hammer and anvil is made observable through removal of residual structure. Then a highspeed-camera is used to observe the behaviour of hammer and anvil. In the analysis of the video, two new states are visible. In Figure 8, the real system behaviour in the states from the initial C&C²-Sequence model from Figure 6 is shown. It is extended as an unknown behaviour is detected and the new states are marked in yellow as state 5.1 "second impact" and state 5.2 "second spring compression". In state 5.1, the hammer hits the anvil at low speed with its edge and causes a small impulse. In state 5.2 it is pushed back a few millimetres, before it reaches state 6 and jumps over the anvil.

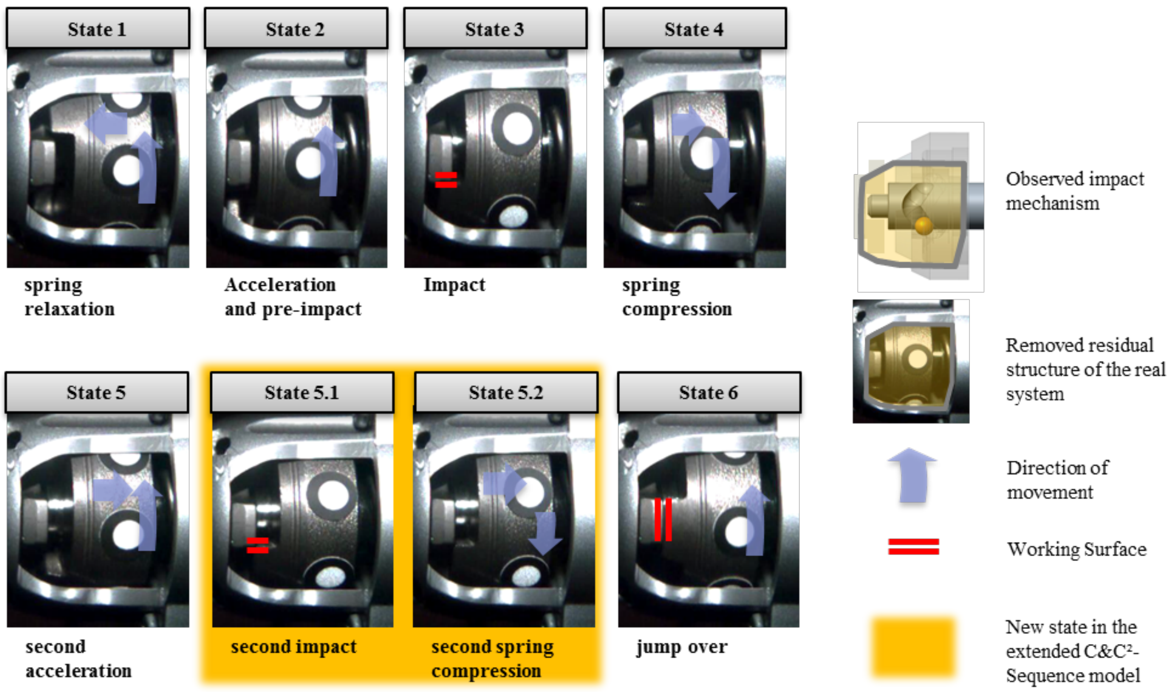

Figure 8: extended sequence model through the overcome observation barrier

With this extended sequence model, the simulation model was improved, as the enhanced data for the movement of the hammer and anvil were integrated and dynamic behaviour of the spring that connects the hammer to the driving shaft could be determined in higher detail than before. Figure 9 shows the output torque of the simulated anvil.

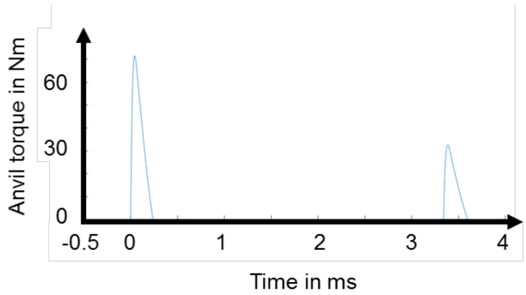

Figure 9: Anvil torque output of the optimised simulation model

The improved simulation model contains the second impact and therefore enables a more precise prediction of the behaviour of the impact wrench.

4 Discussion

The qualitative definition of system states through the C&C²-Sequence model enabled a lean parametrisation of the simulation model, as the system analysis could be focused on single states instead of considering the whole sequence. When the unknown system behaviour was identified, the C&C²-Sequence model was extended and the additional states could be integrated into the simulation. Therefore, the research question can be answered the following way: The C&C²-Approach can be used as a structured approach to identify, describe and verify relations of dynamic system behaviour and parameters of the embodiment. However this statement is based only on the investigation of the impact wrench. The transferability has to be investigated in other cases of modelling of dynamic systems.
While modelling these states, a limitation of the C&C²-Approach was identified, as the states mostly didn't change through emerging or disbanding key elements but through massive changes of their properties like moving direction, acceleration etc. Emerging and disbanding key elements can be displayed clearly, however, there are no defined elements to visualise changing of properties, especially if the properties are state-bound. The coloured arrows are often used (see also (Albers & Wintergerst, 2014)), however they are not defined within the C&C²-Approach.

5 Conclusion and outlook

The structured investigation of the impact wrench lead to better understanding of its dynamic behaviour. With the improved simulation model, the real dynamic system behaviour can be modelled with more precision. On this basis, someday the range of application for impact wrenches might be increased through better prediction of the preload force of a screw connection based on improved simulation models of the power tool and its environment. A limit of the C&C²-Approach has been discovered which creates potential for further research in modelling of dynamic system behaviour. The validation of the structured approach has to be done through investigation of other dynamic systems.

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