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Trajectory planning and tracking control for the temperature distribution in a deep drawing tool

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ABSTRACT

The deep drawing process and the resulting product quality essentially rely on the temperature distribution inside the tool. For temperature manipulation and control a flatness-based design technique for thermal trajectory planning and feedforward control for a deep drawing tool is developed based on a distributed parameter system description. Heating cartridges, that are embedded into the tool structure, serve as actuators to insert energy into the system with the desire to transfer the spatial-temporal temperature distribution from an initial to a desired final stationary profile. To address the complex-shaped geometry of the tool a high-order finite element (FE) approximation is deduced and combined with model-order reduction techniques to determine a sufficiently low order system representation that is applicable for optimal actuator placement. For this, a mixed-integer optimization problem is formulated based on a particular reduced-order formulation of the controllability Gramian. The resulting actuator configuration is exploited for flatness-based trajectory planning by constructing a virtual output that differentially parametrizes any system state and input. This implies a particularly intuitive approach to solve the thermal trajectory planning problem. Convergence of the differential parametrization is analyzed in the continuous limit as the finite element approximation approaches the continuum model. Re-summation techniques are integrated into the design to enhance the domain of applicability of the approach. The feedforward control is combined with industry-standardized proportional-integral-derivative (PID) output error feedback control within the so-called two-degree-of-freedom (2DOF) control concept. Simulation and experimental results obtained for a fully equipped forming tool are presented and confirm the applicability of the proposed design technique and the tracking performance. In addition, the results of this paper present a first experimental validation of flatness-based trajectory planning for thermal systems with three-dimensional spatial domain.

1. Introduction

The demand for zero failure production at increased shape complexity, quality standards and high throughput makes the production of car bodies a challenging field of application for control systems engineering. Within the production process deep drawing can be identified as one of the essential steps. Herein, a metal sheet (blank) is drawn into a die by punch to achieve plastic sheet forming as it can be seen in Fig. 1. The blank holder fixes the blank in the outer part, which results in an restraining force that controls the deep drawing process. The restraining force is mostly influenced by the blank holder force and friction so that most of the process-related heat arises in the blank holder area. The forming process depends on a rather large number of process and material parameters that typically vary during operation and influence shape sharpness and forming quality (Doege, Hütte, Kröff, & Strache, 1998). The influence parameters can be classified in disturbance, input and state variables. The disturbance variables in general summarize any contribution or influence factor, respectively, to the sheet such as material parameters, lubricant or the sheet size. The press parameters and the actuators in the tool can be seen as the input variables. The temperature in the tool parts are seen as state variables (Faa, 2009). In combination with the successive reduction of the production window it follows that even small deviations from the nominal design state may lead to quality issues and even defects. Therefore adjustments of the control variables are required, for example the blank holder force (Anja Neumann & Hortig, 2011), which in general are not automated but performed manually by a worker and result in downtime of the press line. Mechatronic components that withstand the

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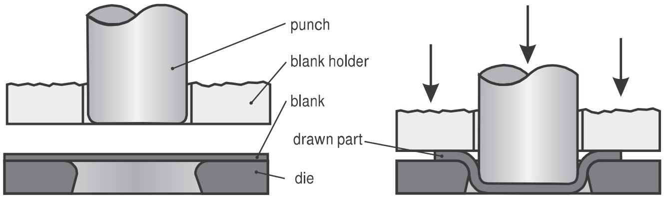

Fig. 1. Deep drawing process of a bowl. Before (left) and after (right) the deep drawing process (Schuler, 1998).

rough environment of the press, for example oil, high accelerations caused by the high forces and impacts are rare and expensive. Caused by the high investments for a press line downtime means high costs and should be avoided.

One crucial process variable is the process-related temperature as observed already in 1925, see for example (Farren & Taylor, 1925), which depends primarily on the tribology system between the tool and the blank, the plasticity of the blank material and the thermoelastic properties of the tool. Typically, the temperature increases during the production process caused by friction and plastic deformation of the metal sheet until an equilibrium is reached. Hence, during production interruptions the tool is cooling down. Every deep drawing process is unique because of the shape, the tool stiffness and the blank geometry. Until now the complexity of the temperature influence and the interactions significantly complicate the development of an appropriate process simulation model. This presently prevents a reliable forecast of the temperature evolution and the interaction between the different influence and exchange factors. A first approach to predict the evolution of the tool temperature after several strokes can be found in Lorzenz and Emrich (2013). Here, a nonlinear CPU-intensive coupled (mechanical and thermal) finite elements simulation of the deep drawing process is executed in the first step. In the second step the average of the heat flow of the deep drawing process is multiply used as a constant boundary condition of a simple heat simulation of the tool.

However, experience yields that a deviation of more than ±10 K of the tool temperature from the operating point may already lead to defects. Experiments show that if temperature related defects are detected in the press shop, appropriate tool heating before production start improves production quality. For further information of the temperature effect on the deep drawing process, see Böhm, Struck, Matveev, Meurer, and Dagen (2013) and the references therein. In order to realize suitable tool heating, experiments at the press shop of Volkswagen AG with a tool equipped with heating cartridges have shown that standard industrialized PI or PID control units are incapable of achieving the desired performance and accuracy in a fixed time span. Thereby additional constraints are imposed by a rather narrow realization window for the desired temperature set point change and the required temperature accuracy since excessively high or low tool temperatures at the production start can deteriorate the process (Böhm et al., 2013). As a result, a sophisticated trajectory planning and control strategy is needed that takes into account the geometric extension of the tool and the resulting spatial-temporal temperature evolution to realize desired temperature profiles in selected areas of the tool within a fixed time span.

To address this issue subsequently a flatness-based design technique is developed for thermal trajectory planning in the deep drawing tool. Flatness implies that system states, inputs and outputs can be parametrized by means of a flat output and its time-derivatives up to a problem dependent order (Fliess, Lévine, Martin, & Rouchon, 1995). This property has important implications for control design (Rothfuß, 1997). Given finite-dimensional flat systems governed by nonlinear ordinary differentially equations this property implies the exact feedback linearization by means of quasi-static feedback control (Delaleau & Rudolph, 1998). In addition, the parametrization allows a particularly simple but systematic solution to the trajectory planning problem, that is the design of a feedforward or open-loop control, respectively, such that the controlled variables of the system follow prescribed desired reference trajectories. By assigning suitable desired trajectories for the flat output the open-loop control and the respective state (and output) trajectory can be directly computed from the parametrization without the integration of any differential equation. This design principle can be adapted to distributed parameter systems governed by partial differential equations (PDEs). Due to the different input configurations with manipulated variables entering the system at the boundary or within the spatial domain different techniques are available for the analysis and evaluation of the flatness property. For boundary controlled linear PDEs this includes operational calculus (Fliess, Mounier, Rouchon, & Rudolph, 1997; Meurer et al., 2008; Petit & Rouchon, 2001, 2002; Rudolph & Woittennek, 2008; Woittennek & Rudolph, 2003), spectral analysis (Becker & Meurer, 2007; Meurer, 2013) and power series (Dunbar, Petit, Rouchon, & Martin, 2003; Laroche, Martin, & Rouchon, 2000; Lynch & Rudolph, 2002). The latter approach enables to also address PDEs with polynomial nonlinearities, where also divergent parametrization can be incorporated by making use of so-called re-summation techniques (Lynch & Rudolph, 2002; Meurer & Zeitz, 2004, 2005). Recent extensions in Schörkhuber, Meurer, and Jüngel (2013) generalize these results to rather large classes of nonlinearities by exploiting formal integration and successive approximation. Flatness-based trajectory planning can be furthermore extended to PDEs with higher-dimensional spatial domains with the control located at the domain's boundary (Meurer & Kugi, 2009; Meurer, 2011; Petit & Rouchon, 2002, 2005; Rudolph, 2003) or interior to the domain (Meurer & Saidani, 2012; Meurer, 2013).

In order to address deviations from nominal conditions, model errors and exogenous disturbances acting on the system the flatness-based open-loop controller needs to be augmented by a suitable feedback control strategy ensuring robustness and closed-loop stability. Taking into account that flatness-based trajectory planning directly yields corresponding desired state and input trajectories solving the system equations it suffices to design the feedback controller for the resulting distributed parameter tracking error dynamics. This results in a two-degree-of-freedom control concept for PDE systems that in addition to theoretical contributions taking into account the combination of flatness with PID output feedback control (Meurer & Zeitz, 2004) or backstepping (Meurer & Kugi, 2011; Meurer, 2011b, 2013) is also validated experimentally for beam and plate structures (Meurer et al., 2008; Schröck, 2012).

These techniques will in the following serve as the methodic basis for the solution of the trajectory planning and tracking control problem for the deep drawing tool schematically illustrated in Fig. 2. Recalling from above that active heat-up of the tool has direct implications on product quality it is desired to realize a predefined spatial-temporal temperature transition path for the tool with a particular focus on the depicted blankholder area eventually reaching a steady-state temperature distribution. This control problem is severely complicated by the complex-shaped geometry of the tool defining the spatial domain. Energy is inserted into the system by heating cartridges that are embedded into the structure by making use of techniques for optimal actuator placement. Flatness is exploited for trajectory planning and open-loop control. For this, the approach presented in Meurer (2011a) and further generalized in Meurer (2013) is combined with a finite element approximation of the PDE governing the temperature evolution in the tool. With this early-lumping