Validation of Part Holder Models of Car Body Upper Line Dies for Return Stroke Loads

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Abstract. In modern press shops, the latest press technology is used to meet today’s efficiency requirements of sheet metal body part production. Thus, for example, servomechanical press ram drives enable optimized process control through configurable motion profiles of the ram, resulting in increased stroke rates and output of the press line. However, the acceleration of moving masses arising during post-forming operations of line dies can lead to critical loads for the upper die and press ram drive. Especially the part holder of line dies causes dynamic loads when being accelerated during the return stroke. In this regard, this paper deals with the validation of dynamic part holder models on the basis of experimental data obtained by a prototype tool. Finally, design specifications could be defined using the validated dynamic models, enabling the process windows of line dies to be extended in future for robust high-speed production processes in modern press shops.

1. Introduction
A permanent challenge for press shops in the automotive industry involves continually increasing the efficiency of production processes or the press line output for sheet metal part manufacturing. For this reason, servo-mechanical driven presses are increasingly used today, as the process window during the production of large car body parts can be significantly enlarged compared to conventional press technologies [1]. The part and geometry specific characterization of the ram motion of servomechanical driven presses enables new process kinematics and reduces the total process cycle time. Due to this, the press line output can be increased without compromising part quality. For example, the ram speed can be reduced during a forming or cutting process, followed by a return stroke with increased velocity. Here, the servo-mechanical return stroke velocities can considerably exceed those of conventional press kinematics, which in turn exposes moving masses such as car body upper line dies to higher accelerations [2]. However, due to this acceleration of incorporated part holders, critical, shock-like loads occur during the return stroke. Part holder return is delayed compared to the ram movement, causing a difference in velocity between the part holder and the ram. In this respect, figure 1 shows a simplified acceleration of a part holder during the return stroke. The dynamic impact load transferred into die structure must be taken into account when dimensioning the maximum stroke rate of the die, as resulting reaction forces are transferred to the upper die and its clamping elements [1]. The occurring loads can lead to increased wear of tool and press guiding elements as well as to structural damage of the die or kinematics of the press [3].
For smoothing the part holder acceleration, various concepts of part holder suspension and part holder damping are specified in the design of line dies [4]. The damping concepts consist of elastomer spring elements and positioning of retaining pins. In particular, elastomer compression springs are suited for compensating dynamic loads due to their internal damping and viscoelastic behavior. Thus such elastomer spring elements are also referred to as "damping elements" [3].

The part holder acceleration during the ram return stroke, shown in figure 2, is characterized by the initial impact and subsequent oscillations. The oscillations are interrupted by flight phases depending on the part holder load. By predicting the dynamic loads occurring during a characteristic part holder acceleration, part production processes can be robustly designed. Production downtime due to tool failures can be prevented by dimensioning the damping concept according to production parameters [5]. However, such a dimensioning requires extensive research work regarding the behavior of damping elements and the development of rheological models for the calculation of dynamic loads resulting from mass acceleration.

In this respect, Swidergal performed coupled multi-body simulations for part holder vibrations analysis, showing that the elastic behavior of the accelerated part holder is of particular importance for calculating the resulting dynamic loads [6, 7]. In order to implement hysteresis cycles of the damping elements within the multi-body simulation, a rheological model of the elastomer elements was used [8]. In addition to the dynamic simulation of the tool components, Thumann and Swidergal's work also focused on analyses of the dynamic behavior of the damping elements [9, 10]. Due to the elastomer
elements' chemical composition, they exhibit non-linear characteristics under dynamic pressure load. Damping element manufacturers usually provide static characteristics for damping elements, which are not sufficient to describe their dynamic behavior. Since the manufacturer's data on the characteristics are insufficient to derive realistic models for simulation purposes, Thumann carried out intense experiments for determining material data and developed a corresponding material data model on the basis of the measurements [10].

2. Approach

Swidergal and Thumann focussed their work on elaborating general material data for damping elements. The nonlinear characteristics of the part holder damping elements lead to complex material models estimating their general behavior. The definition of such models requires intense effort and testing. Such a complex material model represents a much larger operating scope than occurring during part holder acceleration. Decreasing model complexity, a process data-driven modeling approach can estimate part holder behavior based on real part holder acceleration data. Focussing on the part holder acceleration allows the implementation of dynamic material models with less effort. Due to the specific operating and design parameters, like the number and type of damping elements, it is necessary to develop a holistic process-related database. By defining characteristic parameters based on part holder process data, the resulting model is improving current conservative models for tool design. The part holder operating points are specified by their characteristic impact velocity, part holder mass, and damping concept. This is based on the concept that, due to the limited operating points, compared to a general material model, a process data-driven model represents the corresponding operation points more precisely. For this reason, the research work presented in this paper is focussing on the evaluation of process-related characteristic parameters derived from a real part holder process database. Figure 3 shows the data-driven approach for estimating damping element model parameters using an experimental part holder tool to generate the required process data. The data-driven approach is comparing models with increasing complexity to the real part holder system, till the specific behavior is represented.

![Data-driven modeling approach for parameter estimation of dynamic part holder system models, based on experimental data.](image)

Figure 3. Data-driven modeling approach for parameter estimation of dynamic part holder system models, based on experimental data.
The main objective of this approach is the evaluation of rheological models for damping elements based on process data from an experiment tool. The model parameters are estimated by a Parameter Estimation using Matlab Simulink, evaluating, and validating the models [11]. The main goal is to define a suitable dynamic model specified by parameters representing the dynamic behavior of part holder systems. This data-driven approach enables a more precise prediction of part holders’ dynamic behavior, leading to robust tool design. Developed characteristic parameters for the design of dynamic part holder systems enable servo press potentials, by precisely predicting process loads during part holder acceleration. Therefore, higher stroke rates and an efficient production process in-line dies can be established [5].

In the following sections, the validation of two different rheological models for elastomer damping elements is shown. Furthermore, the models’ parameters are estimated by measurements from an experimental part holder tool. The paper concludes with a discussion of gained results in terms of further research demand.

3. Rheological modeling of part holder acceleration
In order to model the dynamic behavior of the characteristic part holder acceleration, damping elements were described by using the rheological multi-parameter models, according to Kelvin-Voigt and Zener. Rheological models are composed of idealized material properties in terms of elasticity, viscosity, and plasticity. The rheological models’ characteristics are divided into linear idealized Newtonian and Hookian elements [12]. Possible rheological models for describing part holder damping elements’ behavior differ in their complexity and number of parameters. Two different rheological models are evaluated in this research work: the Kelvin-Voigt model and the Zener model, shown in figure 4 and figure 5.

![Figure 4. Representation of the Kelvin-Voigt model by Hookian and Newtonian elements.](image1)

![Figure 5. Representation of the Zener model by Hookian and Newtonian elements.](image2)

The Kelvin-Voigt model, also called a Kelvin-Voigt body, is used for describing materials with creep behavior. Therefore, this model represents the behavior of polymers. The Kelvin-Voigt model is described by the parallel connection of a Hookian and a Newtonian element, as shown in table 1. Two specific parameters do define the dynamic behavior of the Kelvin-Voigt model $d$, $k$ [12, 13]. The Zener model extends the Kelvin-Voigt model by an additional Hookian element (see table 1) resulting in a three-parameter model. Due to the increased number of parameters $d$, $k_1$, $k_2$, the Zener model enables the description of more complex material behavior, especially of polymers with viscoelastic behavior [14–16].
Table 1. Comparison of the Kelvin-Voigt model and the Zener model with each characteristic parameters and differential equations.

| Parameters: \(d, k\) | Parameters: \(d, k_1, k_2\) |
|-------------------------|--------------------------|
| Differential Equation:  | Differential Equation:   |
| \(m\ddot{x} + d\dot{x} + kx = 0\)  | \(\dot{x}_1 d - k_2 \cdot (x_1 - x_2) = 0\)  |
|                         | \(m\ddot{x}_2 + k_1 \cdot x_2 - k_2 \cdot (x_1 - x_2) = 0\) |

The characteristic behavior of the described models is defined by the respective parameters. The parameters can be estimated by different kinds of material analysis. In the following, the experimental part holder data-driven approach is described, estimating the rheological model parameters.

4. Estimating model parameters

Using the data-driven modeling approach based on the experimental part holder tool, the characteristic parameters of the differential equations of the rheological models investigated are solved by means of experimental data. For this purpose, the spring-damper models were defined in MatLab Simulink. By using the measurement results, described in the following section 5, in combination with the Parameter Estimation from MatLab Simulink, the characteristic parameters of the models could be approximated. The model parameters can be calculated locally or globally using different sets of experimental measurement results. MatLab Simulink uses error statistics to identify outliers, whereby the error \(e\) is calculated by measuring the difference between system output and measured data. The used cost function \(F(x)\), shown in table 2, serves as a Sum Squared Error. [11]

| Nonoutliers Cost Function | Outliers Cost Function |
|---------------------------|-----------------------|
| \(F(x) = \sum_{t \in N} e(t) \times e(t)\) (5) | \(F(x) = \sum_{t \in O} w \times |e(t)|\) (6) |
| \(N \triangleq \text{nonoutliers samples}\) | \(O \triangleq \text{outliers samples, } w \triangleq \text{linear weight}\) |

In the case of a local Parameter Estimation, the model characteristics are determined separately for each part holder operating point and adjusted by the measured data. Therefore, a specific parameter set is generated for each operating point, representing the optimum for the given measurement result. In contrast, a global Parameter Estimation calculates the specific model parameters concerning all selected input measurements. By minimizing the individual deviation of the estimated and measured outputs, a global parameter set is generated. Regarding the range of operating points and the specific rheological model, a global parameter set results in an optimum description of the damping elements’ material behavior being used part holder acceleration.

Experimental data are required to enable the definition of suitable parameters for the selected models. For this purpose, corresponding measurements were performed by use of an experimental part holder tool, as described in the following section.

5. Part holder measurements for estimating model parameters

In the experiments described in the following, characteristic part holder accelerations were measured under series conditions by using the experimental tool shown in figure 6. Subsequently, specific operation parameters for damping elements could be determined based on these measurements [2]. It should be noted that the experiments for the data-driven validation of rheological models must be conducted under series production conditions. Only in this way, the dynamic characteristic parameters
of the differential equations for damping element models can be defined and adapted to the various operating parameters such as part holder mass and impact velocity.

Figure 6. Experimental tool design a) and realized experimental part holder tool b) for acceleration measurement during the return stroke of the ram [2].

The experimental tool was operated in a servo mechanical press according to figure 6 and table 3. The stroke rate was varied in the complete range between 10 to 18 strokes per minute. The stroke rate was incremented by steps of two strokes per minute. Furthermore, the weight of the part holder was designed to be variable. For the presented experimental design, three different masses can be realized by mounting additional weights symmetrically onto the part holder.

Table 3. Measured experimental part holder tool operating points for parameter estimation, regarding stroke rate, part holder mass and damping concept.

| Stroke rate                  | Part holder mass | Damping element        | Part holder stroke     |
|-----------------------------|------------------|------------------------|------------------------|
| 10 to 18 increments         | 328 kg           | One central damping element | Constant part holder stroke |
| of two strokes per minute   | 435.5 kg         |                        |                        |
|                             | 543 kg           |                        |                        |

During the return stroke of ram, a central retaining bolt accelerated the part holder inside the upper die. The part holder stroke was kept constant throughout all measurements. The experimental tool was equipped with different measuring equipment as described in table 4.

Table 4. Evaluated sensors and measured values regarding relevant input for parameter estimation.

| Sensor                        | Measured value | Regarding                  |
|------------------------------|----------------|---------------------------|
| Cable Transducer:            |                |                           |
| ASM WS17KT-2000              | mm             | Ram position and velocity |
| Acceleration Transducer:     |                |                           |
| HBM B12/200                  | m/s²           | Part holder acceleration  |
| Displacement Transducer:     |                |                           |
| HBM WA/50MM-MT               | mm             | Damping element displacement |
| Force Washer:                |                |                           |
| HBM KMR/400KN                | kN             | Reaction force            |
An operating point is defined by the impact speed of the upper die, the part holder mass, and the specific damping element used. Therefore, the measurement results could be assigned to specific operating parameters. The specifications and characteristic values provided by the damping element manufacturers specify the maximum operating range for evaluated operating points. Figure 7 shows, for example, the maximum part holder accelerations in relation to part holder mass and impact velocity, with circles indicating a set of chosen parameters. Statistical validation required a minimum of at least three measured part holder accelerations for each set of parameters. Due to the very precise correspondence of the experimental data at one operating point over several experiments, the scatter of the maximum values can be considered negligible.

**Figure 7.** Measured maximum part holder acceleration for different operation points (blue circles) regarding part holder mass and part holder impact velocity of the experimental tool.

Based on the measurement results, it is possible to simulate corresponding operating points with the rheological models. The characteristic values can subsequently be estimated, as described in the next section. In the following, results gained with the Kelvin-Voigt and the Zener model are compared and discussed.

6. Parameter Estimation Results

In the following section, the process data measured with the experimental part holder tool served as input data for the Parameter Estimation. By comparing the estimation results obtained with the different rheological models, the best fitting parameters and models could be evaluated, regarding the described error function.

Comparing measurement results of the experimental tool, to the output data of the rheological Matlab Simulink models, characteristic parameters are estimated iteratively by using Parameter Estimation with corresponding input parameters. Characteristic parameters can be determined locally or globally for the two rheological models, shown in section 3.

Figure 8 and figure 9 represent examples of two specific operation points. The estimated output curves were calculated by local and global Parameter Estimation. Two measurements are shown as examples, which demonstrate significant differences in the impact speeds for the same part holder mass. The experiments are defined as experiment 1 and experiment 2. The Parameter Estimation for the Kelvin-Voigt model was carried out locally for both experiments in figure 8 a) and b).
Figure 8. Comparison of local Parameter Estimation of the Kelvin-Voigt model for two example experiments a) 1 and b) 2.

By using the estimated parameters from experiment 1 for the operating points in experiment 2, as shown in figure 8 b), it is evident that a local estimation with the respective operating parameters may deliver a more accurate result. It also illustrates that a local approximation of the parameters is not sufficiently accurate to specify a holistic description of the damping element in a dynamic part holder system. If the estimation is performed globally, shown in figure 9, the advantage of the Zener model over the Kelvin-Voigt model is evident. For experiment 1 shown in figure 9, the Zener model provides a more accurate representation of the maximum acceleration, the flight phase, and the period of oscillation. The same behavior occurs for the other globally analyzed experiments.

Figure 9. Comparison of global Parameter Estimation of the Kelvin-Voigt model to the Zener model for experiment 2.

In conclusion, both models can describe the part holder damping elements’ behavior. The Kelvin-Voigt model provides sufficient modeling of the acceleration at a local Parameter Estimation, which means, that no generally valid global parameters can be defined. However, the Zener model is more
accurate regarding the behavior of the part holder acceleration in global Parameter Estimation. The global Zener model enables the estimation of constant parameters for the part holder damping element with sufficient accuracy and enables the possibility to design and predict the behavior in series production. Based on the parallel connection of elastomer elements in the die, a global model also allows the prediction of complex die behavior. Here, the mass and the reaction forces must be distributed evenly over the elements, which can be ensured by the die design. By providing an analytical calculation, for example, process-critical loads occurring during part holder operation can be estimated.

7. Conclusion and outlook
The presented process data-driven approach allows the definition of characteristic values for the description of damping elements in dynamic part holder systems. By evaluating validation experiments, the prediction accuracy of models is improved. The two investigated models show that the representation of operating points is possible with the increasing complexity of the model and corresponding global Parameter Estimation. Through its increased complexity, the Zener model enables a description of the behavior over the considered operating range with global estimation.

Following the analytical description, the resulting rheological models can additionally be implemented in simulation software. Therefore, for example, multi-body simulations with rigid as well as flexible bodies can be performed based on the defined models and characteristic values. Tool and press loads can be estimated at an early stage, and design adjustments or general guidelines can be defined. Consequently, higher stroke rates and efficient production and design processes of line dies are enabled.

The realization of the experimental part holder investigations represents an additional effort in the application of new damping elements. For this purpose, the measurement and evaluation through specific experimental setups and models are necessary. Extensive investigation of additional rheological models for the specific description of the dynamic part holder system properties offers potential for optimization. Furthermore, an extension of the operating points, as well as a long-term investigation, allows an enhancement of the possible range for model application.

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