Modelling of dynamic loads during series operation for optimisation of part holder design

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Abstract. Energy and resource efficiency today are fundamental challenges in production technology, which also arise in the production of sheet metal body parts when using state-of-the-art press technology. Since sheet metal forming processes are becoming more and more complex due to modern design of car body shape, the tools for producing body parts are increasing in size and modern press technology is developing correspondingly faster. Simultaneously, produced tools for new car models must withstand applied process related loads emerging during lead time of model to ensure a robust production process. Based on the increase in productivity supported by servo press technology of today and resulting higher demands on required tool strength, part holders assembled in large line dies in particular belong to critical tool components. In this paper, an optimization concept for part holder design is presented. Higher acceleration of press ram and upper tool results into higher levels of dynamic impacts, which can lead to critical load cases originating from spatial mass distribution of part holder. Occurring loads are reduced by use of damping elements. The distribution of damping elements into part holder structures is optimised according to the mass distribution of the part holder and the design of the upper die. For this purpose, dynamic effects of the tool were modelled based on analytical models and verified by multi-body simulations and corresponding stress calculations. The application of dynamic load characteristics of tool components thereby allow realistic modelling of distributed mass and force effects. Finally, simulation results were validated on the basis of tests under series production conditions.

1. Introduction
Today’s sheet metal forming production challenges require optimization of manufacturing processes with regard to cost and time savings as well as quality improvement. In this respect, the productivity of sheet metal component production is increased, for example, by continuously advancing machines and systems in terms of productivity. Complex shaped, large parts made of sheet metal for car body construction are nowadays produced on multi-stage press lines. Moreover, the introduction of servo press technology leads to more efficient forming processes, as the flexibility of the torque motors used enables new process and stroke curve designs [1]. Due to the increased stroke rates and ram speeds, the forming tools are loaded more and more dynamically because they are accelerated, decelerated and moved at higher ram speeds compared to last decades. Especially tools for trimming and post-forming operations carrying a part holder in the upper die are subjected to high loads during return stroke of the tool. Here, particularly high dynamic loads occur when this part holder is accelerated to upper die speed
by a carrier device during the return stroke movement. In order to reduce the engagement time of the part holder, spring and so-called damping elements made of elastomers are therefore integrated within the lifting devices [2]. These elements allow an evenly distributed load and soft damping of the part holder and thus can compensate the corresponding loads or acceleration forces and prevent damage of the tool. The aim of the research work reported about in this paper is to numerically specify the number, type and positioning of such part holder damping elements. The required number of elements is determined by an optimized modelling and dimensioning of analysed damping elements and dynamic loads considering appropriate dynamic spring characteristics. In addition, the numerical investigations involve the modelling of the part holder engagement in order to ensure a uniform distribution of reaction forces. In this way, peak loads are reduced, damage of the load-bearing structure is prevented and tool wear is minimized. During the investigations presented in this paper, the required dimensioning and design models are theoretically derived and experimentally validated.

2. Previous Work
In order to prevent the damage of tools carrying part holders, different concepts of part holder suspension and damping components are used today. When choosing a suitable damping concept, considering the number and distribution of elements, the load-bearing impact in the tool caused by the part holder during its intervention must be considered. The chosen damping concept must be taken into account when dimensioning the stroke rate of the tool [1]. On this basis, the required damping elements are subsequently specified by several parameters such as spring force, spring stroke as well as installation space and stroke rate of the tool [3].

In order to design robust processes even with high part holder masses, Swidergal emphasizes that the dynamic behaviour of the tool and consisting tool components needs to be analysed [4]. Here, special attention must be paid to damping elements and vibrations aiming to avoid damage to the part holder as well as to the upper die parts. For the analysis of the part holder vibrations, calculations have been carried out using the coupled multibody finite element method [4]. Swidergal also investigates influence of high loads caused by servo press technology on cams, in particular those resulting from vibrations of the die components [5]. Thereby, his main objective is to develop light and topologically optimized components based on simulations. In simplified simulations, only a single retaining pin is simulated and validated experimentally. According to Swidergal, the structural behaviour of the part holder design is of particular importance here [6; 7]. For this reason, multi body simulations combined with finite element simulations are performed using the given tool geometries [7]. Furthermore, rheological spring-damper model is used in order to calculate the hysteresis loop of the damping elements [7]. During the calculation, the vibrations of the point of impact and the impact during the return stroke are considered, since these parameters can significantly influence the process. In this way, realistic results can be achieved by the calculations compared to real experiments, even though need for improvement is recognizable in various points [6; 7].

In this respect, there is still potential regarding the simulation of the damping elements, since their non-linear behaviour is only approximated by the simulation models used. In addition, temperature dependency of the damping elements, which influences the process, is not considered so far. On the basis of the calculations performed and an optimization of the models used, numerical process design could improve manufacturing processes and may increase service life of tools. In addition, the aim is to develop lighter tools and to implement energy saving potentials. [6; 7].

Koch described high cyclic loads which cause increased damage to various tool components [8]. In order to achieve the goal of maximising tool lifespan, analytical load collectives are developed which represent increased loads through higher stroke rates. Since existing simulations are available that represent low stroke rates, Koch uses a conversion factor to adjust the load curve. Result of his investigation was that the part holder is deformed in a purely linear-elastic manner and is therefore not damaged. However, the damping elements are heavily loaded, which indicates increased maintenance cycles at higher loads.
Compared to the described dynamic simulation of components, analyses and simulations of the damping elements have become a second focus of research and development. Due to their chemical composition, elastomer elements exhibit complex properties which are influenced by various parameters [9]. According to Thumann, current elastomer manufacturer's specifications does not provide sufficient information in order to ensure realistic modelling of these elements. For this reason, Thumann carried out experiments to determine the required material data for a newly developed model [9]. Subsequently, this model was validated by simulation of corresponding real field experiments.

In addition to the complex material specification, the shape of the damping elements do influence their properties too. Since dampers in assembled into tool structure are ideally loaded axially, Swidergal carried out corresponding loading tests in order to derive material characteristics of specially shaped elements. Based on this, a rheological model for simulations was designed to optimize the calculated behaviour of the elements. Swidergal states that more realistic simulation results can be achieved and the new model allows the implementation of a temperature dependency. [10] New design approaches fundamentally influencing the part holder system can be found in numerous patents [11–14].

### 3. Modelling Approach

Several parameters do define the damping system of a part holder such as size, material and number of elements as well as their position in tool structure. In addition, the required minimum number of damping elements indeed do specify the design of part holder damping. For this purpose, the oscillation system can be simplified as shown in Figure 1.

![Image](image.png)

**Figure 1.** Modelling of part holder dynamic systems, shown on the left, with a simplified spring-damping system, shown on the right, and resulting parameter relations.

When observing the acceleration model of the damping elements, it can be stated that the occurring acceleration is significantly influenced by the deflection of the elements, which in turn depends on the material characteristics and the geometry. As a result, the allowed maximum displacement mainly determines the load applied onto the upper part and thus provides a damage criterion for the entire set of elements. This means that the fewer springs installed, the lower the overall load, caused by a softer damping system.

As already mentioned, the manufacturer's specifications regarding spring and damping properties are insufficient for the numerical design of damping systems, as these are static characteristics. Therefore, the research work reported about in this paper aims to define realistic spring properties which allow a maximum allowable spring displacement of the system. For this reason, drop tower experiments were carried out in order to determine dynamic spring characteristic values such as dynamic spring rates, maximum deflections and maximum stroke rates.

The maximum deflection of the various elements as well as maximum stroke rates are defined by the investigated dynamic characteristic curves and considering the recommendation of the manufacturers. In addition, their design guidelines for elastomer springs are taken into account. The stroke rate,
geometry, material and setting behaviour are taken into account accordingly to ensure fatigue strength [2].

By adjusting the spring characteristic values, compared to the manufacturers given static properties, and evaluating the design by series measurements, the required number of dampers can be reduced, compared to existing characteristic values. This is based on higher dynamic spring rates and is illustrated exemplarily in Figure 2. By determining the spring coefficients and maximum deflections, the total load can be reduced. Considering the load occurring per retaining pin, it becomes apparent that the load increases with a decreasing number of damping elements and corresponding retaining pins.

![Figure 2](image-url)  
**Figure 2.** Comparison between static and dynamic properties regarding required number of elements with safety. Number of elements relative to maximum required number.

Increasing loads per retaining pin is reflected in the upper die and therefore must be reduced to a minimum by a suitable distribution of the damping elements. With this regard, simulations were carried out using common CAD system Siemens NX in order to derive a design methodology for the distribution of the required retaining pins. Here, the aim was to select the arrangement of the suspension points on the part holder in a way that resulting reaction force is distributed as evenly as possible and that minimal tilting is achieved when the retaining pins are entrained. Additionally the upper die influences the retaining pin positioning by its structural design.

3.1. **Configuration of damping elements - part holder**

In order to derive guidelines for the design, static and dynamic simulations of both a simplified model and a real part holder geometry were performed. Static simulations consider bending separately from dynamic effects of mass inertia. Statically, the tilting of the part holder and the deflection of the elements can be simulated realistically. In addition, the simulation results regarding to the position of the damping centre to the mass centre showed that if the geometry tilts due to uneven positioning of the dampers, additional reaction forces are rising accordingly. This confirms the influence of the damping centre, which is influencing the damping system according to the literature, and allows the definition of maximum deviations of the mass and damping centres [2]. Table 1 shows the exemplary relation between the two centres, based on static simulation of a part holder geometry. The damping centre describes the position of the resulting force, which is generated by the damping elements. Since $\Delta s$ describes the absolute deviation of the centers, the results do not have a linear relationship. Instead, symmetries and size ratios of the part holder can have a positive as well as a negative effect on the reaction force deviation.

In addition, an influence of the mass gradient in the part holder on the occurring forces can be determined, since the part holder bends the most in the area of the largest mass concentration. This structural bending causes an additional deflection of the damping elements locally influencing the force distribution. By appropriately adjusting the damping elements in the surrounding area of the largest mass accumulation, this bending effect can be compensated. A geometrically uniform distribution of damping elements supports this effect.

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The conclusions of simulation results of the simplified geometries were finally transferred to real part holder geometries and experimentally verified. Since the simulation results of the simplified part holders correspond to those of the real geometry, conclusions could be transferred between the models. By modelling real part holder geometries, also the influence of the part holder guides on the reaction force distribution was investigated. As a result, it was observed that the reaction forces are distributed more evenly due to the reduced tilting of the part holder. However, this guiding effect will not be taken into account in the following, since the load should be reduced on the guides as well as the tilting. In this way the wear of guides is reduced, less load is transferred to the upper die and a more precise positioning of the part holder is possible.

3.2. Configuration of damping elements - upper die
Besides the part holder geometry and its oscillation behaviour, the strength of the upper die additionally determines the optimal positioning of the damping elements. In order to prevent the upper die from getting damaged due to excessive stresses, an appropriate high distance must be maintained between the retaining pins, as the reduced number of dampers due to dynamic characteristics results in higher loads per retaining pin. In addition, the stresses occurring in the upper die is influenced by the geometry of the upper die, for example by voids and ribbing.

In order to develop an appropriate design specification for positioning damping elements considering to the load on the upper die, static simulations were carried out in several individual models. It is assumed that examined parameters can be evaluated separately and their influence can be superposed. In the final simulation step, the simulation results are verified on real upper die geometries in order to weight the individual parameters accordingly. The modelling includes analysis of distance between the retaining pins, clearance size and their distance as well as influence of ribbing and its positioning. Different simulation models and the validation with an upper die can be seen in Figure 3. Strength evaluations were primarily carried out on the basis of the principles of the FKM guideline [15]. Based on empirical data, a scale of up to 75 N/mm² is used as the evaluation criterion.

Table 1. Distance between centre of mass and centre of damping and resulting deviation of reaction forces. Color-coded from green low values to red high values.

| Increasing distance Δs [mm] | ΔF [%] |
|-----------------------------|--------|
| 4                           | 2      |
| 24                          | 18     |
| 27                          | 13     |
| 37                          | 11     |
| 70                          | 16     |
| 79                          | 31     |
| 85                          | 30     |
| 94                          | 36     |
| 125                         | 59     |
| 134                         | 59     |
| 146                         | 44     |
| 199                         | 72     |
| 208                         | 124    |
| 218                         | 91     |
| 270                         | 24     |
| 307                         | 88     |
| 419                         | 121    |
| 433                         | 175    |

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Figure 3. Approach to derive a weighting function from real upper die geometry (left). Simplified models (right) were validated and weighted by real upper die simulations.
In summary, it could be established by the simplified models, that there is a correlation between the distance of the pins, their load and the resulting die stresses. Similar effects could be worked out for the distance and the size of clearances. The load can be reduced by up to 50 % by ribbing in the immediate surrounding of the retaining pin thread. In order to verify the results obtained from the example geometries and to adjust them with respect to their magnitude, real upper die geometries are simulated. Based on these results, the previously obtained results can be classified and evaluated. Clearances in the immediate area are of minor importance. They can influence local load peaks, but depending on position and ribbing in the upper die they are not of significant relevance, so the distance between two retaining pins is of crucial significance. The position of the retaining pins in the upper part is also a matter of relevance. In the centre of the upper die it is the weakest due to its lateral suspension and can show high deformations.

Overall, a minimum distance can be derived for retaining pins. This dimension can be used as a basis for additional clearance distances. Furthermore the arrangement of pins in the centre of the upper die can be restricted.

4. Dynamic Part Holder Simulation and Validation

The part holder system is analysed using dynamic models to analyse the damping process. In turn, transition is made from simplified geometries to real geometries. As already mentioned, the simplified model is based on the assumption that the modelling of a single retaining pin can achieve sufficiently good results.

Simulations are carried out with rigid bodies and a constant driving speed. The detailed model is designed accordingly with a real part holder geometry. An exemplary part holder structure is shown in Figure 4. The model offers the possibility of simulating both a guided and a non-guided part holder. In this way, effects of mass inertia and damping distribution can be analysed, as well as the influence of guide tolerances.

The dynamic effects cause the geometry to tilt when the part holder oscillates. This results in an uneven engagement of the damping elements and therefore in deviating accelerations and forces. Figure 5 shows the reaction forces of the retaining pins for an according simulation. Further simulations have shown that the approach of the damping centre to the mass centre favours the uniform, initial movement of the part holder. Following impacts can result in uneven reaction forces due to mass inertia and guidance tolerances.

To validate the results of the dynamic simulations, measured data from acceleration and force measurements on part holders from series production is used. Simulations and analytical calculations of the systems were carried out corresponding to production conditions.

In conclusion, the dynamic simulation results are considered positive. Major influences on the behaviour of the part holder movement can be represented and analysed. Measurement results are also
compared with the adapted dynamic analytical calculations. In Table 2, the measurement results for a line die part holder for the inner part of a driver's door are compared with the calculations and simulations. According to the measurements, the adapted analytical calculation model allows a sufficiently accurate prediction of the acceleration and forces, which can be secured against process variations by defined dynamic safety factors. The simulation results differ from the measured results due to overestimated damping values, which resulted from static damping values. By optimizing the dynamic characteristic values in simulation, experimental results can be approximated.

![Simulated part holder reaction forces, relative to maximum force for unguided dynamic simulation.](image)

**Figure 5.** Simulated part holder reaction forces, relative to maximum force for unguided dynamic simulation.

**Table 2.** Comparison of experimental and calculated accelerations for serial production.

|               | Experiment | Static Analytic | Dynamic Analytic | Dynamic Analytic incl. Safety Factor | Dynamic Simulation |
|---------------|------------|-----------------|------------------|--------------------------------------|--------------------|
| 100.00 %      | 71.32 %    | 99.58 %         | 112.04 %         | 87.10 %                              |                    |

5. Conclusion and Outlook

Within the scope of this work, the focus is placed on part holder entrainment in large tools, which has a significant influence on the process-related mechanical loading of tools of line dies due to its impact-like loading at increased speeds.

The developed models presented in this paper allow a reduction of the required damping elements as well as a reduction of the total load in the upper die, by adjusting element properties. To adapt such models, dynamic spring characteristic values were defined and assured with corresponding specific safety factors. In addition, a design specification was derived on the basis of simulations, which favours an even force distribution in the upper die. The modelling of this system and the results from the static simulation were able to be validated and refined by dynamic multi-body simulations. Influence of mass inertia and damping characteristics were considered and transferred to the model and design restrictions. To validate the analytical and simulation results, measurements from series production were used and additionally compared with the results of analytical calculations. In summary, it is stated that the part holder stroke, can be optimised with the aid of the elaborated design and calculation regulations. However, improvements beyond this work can be found. In order to generate realistic and reliable dynamic simulation results, corresponding characteristic values must be used. Furthermore, measurement results from series production are particularly important for validating dynamic simulations.

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