Building a substitute model of a bolster based on experimentally determined deflection

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Abstract. The high design requirements in the production of car body parts necessitate an exact closure of the forming tools in deep drawing processes. The tool closure is directly related to the machine elastic behaviour. To significantly reduce efforts and save time during ramp up of new forming tools, knowledge of the expected machine behaviour should be considered during the virtual development process of the tools. A prerequisite for that is building a validated machine-specific substitute model of the forming press composed of bolster, ram and drawing cushion. In this contribution, a substitute model with the help of finite element analysis (FEA) based on experimentally determined deflection is presented. The deflection measurements are performed by means of a multifunctional press measuring system from Volkswagen.

1. Introduction
The design requirements of car body parts are increasing for outer skin parts as well as structural parts. At the same time, a speed up and cost reduction in the product emergence process is essential to operate successfully in the global competition [1]. The try-out of new forming tools provides a high cost- and time-saving potential. To fulfil the high requirements on the component quality, a precise tool closure is mandatory [2].

Because the elastic tooling behaviour as well as the elastic machine behaviour of the forming press are not considered in the present method planning process, a cost- and time-consuming manual rework process is required until good parts are produced [3]. In practice tooling, the bolster, the ram and the drawing cushion deform elastically under load. Consequently the active surfaces gape apart, which leads to a deficient pressure distribution on the component [4]. To counteract this effect the active surfaces of forming tools are globally cambered [5]. This camber is at present solely based on the experiences of the existing similar forming tools. The objective of current projects at Volkswagen is to quantify the necessary camber in advance to reduce the amount of rework significantly. A prerequisite for the successful prediction of the deformation of the active surfaces is the exact knowledge of the machine behaviour under load. Hence a machine-specific digital twin in the form of a simplified FE-substitute model has to be developed. Basis for such a model is a reproducible dynamic measurement of the forming machine.
2. Press-measurement
The measurement of forming machines has already been examined in a variety of research projects. In many cases, the developed measuring systems were based on VDI 3193-2, VDI 3194-2 and DIN 55189, which determine essential methods for the static measurement of displacements of forming presses under load [5][6][7]. Press-measuring systems were developed, among other things, by Träger [3], Braedel [8], Behrens et al. [9][10], Rühlcke et al. [11], Kunke et al. [12] and Freiherr et al. [13].

With the focus of reproducibility and quick feasibility of dynamic press measurements a multifunctional measurement and load system called press-fingerprint-tool (PFP-tool) [14] was invented by Volkswagen in cooperation with Fraunhofer Institute for Machine Tools and Forming Technology (IWU). Figure 1 shows the CAD-model of the PFP-tool in half open state. The tool was first commissioned in July 2012.

![Figure 1. CAD-model of the press-fingerprint-tool [15].](image)

The measuring tool is constructed in two parts - the lower part which is fastened to the mounting surface of the bolster and the upper part which is fastened to mounting surface of the ram. The load during a stroke is applied by eight independent gas pressure spring assemblies. By changing the filling pressure of the gas pressure springs, the force application can be controlled. With the use of load cells positioned at the upper part of the tool, the occurring forces can be determined over the entire mounting surface of the tool (cf. [4]). Both on the upper and lower tool part bend-resistant CFK-measuring frames are attached, which have an array of tactile measuring sensors mounted on them. The sensors measure the displacement of the base plate of the PFP-tool on the upper and lower tool part. The deflection of the PFP-tool baseplates is identical to the deflection of the mounting surfaces of the bolster and the ram, as the baseplates have less stiffness than the machine. In the four corners of the tool, laser distance meters are used to track the tilting of the ram during a full stroke. The tilting of the die cushion is measured by four sleeves in the corners of the tool. All data is captured and saved in a central measuring computer.

3. Processing and usage of the measurement data
For further usage in FE-simulations the measuring data has to be processed. For this a tool is developed, which semi-automatically evaluates the datasets. First, the raw data is imported and filtered. The effective applied force can be determined by the pressure curve in the gas pressure...
springs. The signals from the tactile measuring sensors in the bottom dead centre of the press from measurements with different total applied forces are combined and linearized. As a result it is possible to determine the deflection behaviour for any load. Figure 2 shows the deflection curves for a bolster of a transfer press from Volkswagen (referred to as press A) at a total load of 10 000 kN. The measuring sensors at the bolster are attached to three measuring bars whereby the highest displacements occur in the middle of the bolster. The two other curves refer to the front or back sides of the bolster. The points with no deflection at ±1850 mm in x-direction are the supports of the measuring frame.

![Deflection curves measured with the PFP-tool at a total load of 10 000 kN.](image)

**Figure 2.** Deflection curves measured with the PFP-tool at a total load of 10 000 kN.

The measurement results are already used to categorize forming presses regarding their deflection behaviour. Thereby the try-out and production presses with similar machine behaviour can be combined for the ramp up of the new tooling which speeds up the process and prevents counterproductive rework. Further, retrofit measures can be evaluated if the press is measured before and after the adjustment work. Also the periodic measurement of presses over the years allows the quantification of the wear on the machine for the first time.

Furthermore, the measurement results are the basis for the digital specification of the machine behavior in form of substitute models for FEA.

### 4. Substitute model of the bolster

The substitute model of the bolster has to reproduce the deflection behaviour of the real bolster as accurately as possible. At the same time, it should be as simple as possible to keep the needed computing power minimal. In Figure 3, the developed FE-substitute model is shown with the simplified base plate of the PFP-tool. All pre- and post-processing is done in LS-PrePost®. The system boundaries for the model are defined by the mounting surface of the bolster and comply with the geometric dimensions of the bolster of press A. The surface of the bolster is modelled with shell elements with thicknesses corresponding to the dimension of the real bolster of press A. The bolster is not segmented but the sleeve holes are modelled. All shell elements are modelled with the same modulus of elasticity. At the four corner nodes, the surface is rigidly supported. At the edges, the model is supported by linear-elastic springs, the free ends of which are rigidly supported. The springs at the longer edges form a spring assembly and are modelled with the same spring constant. Likewise, the springs at the shorter edges form an assembly.
Figure 3. Developed FE-substitute model of the bolster of press A.

The simplified base plate of the lower part of the PFP-tool fastened to the bolster model. Similar to the experiment, the load is applied through pressure on the gas pressure springs. The pressure curve for the gas pressure springs is in line with the experiment. The solver used is LS-DYNA®. To facilitate the model to reproduce the real behaviour of the bolster of press A, the spring constants of both spring assemblies and the elastic modulus of the shell elements are parameterized. The prepared deflection values at the positions of the tactile measuring sensors of the PFP-tool are the target figures for the optimization. With LS-OPT®, the three mentioned parameters are optimized iteratively in prescribed boundaries until the termination criterion is reached.

In Figure 4, the result of the optimization with a symmetrical force application of 10000 kN is shown. The continuous lines depict the deflection curves measured with the PFP-tool on press A. The dotted lines depict the numerically calculated deflection. In total, three curves for each of the three measuring bars are plotted. Since the load is applied symmetrically, the displacements at the front and back of the bolster are almost similar.

Figure 4. Optimization result based on measuring results of the PFP-tool at 10000 kN.
In the range \(-800 \text{ mm} < x < +800 \text{ mm}\), the numerically calculated curves are very close to the measured values. Especially the points at the measuring bar in the middle are almost congruent. The mean squared error is 0.00143. The elastic modulus of the shell elements is 182,900 N/mm\(^2\) and the spring constants for the long and short assemblies are 4,000,000 N/mm and 3,000,000 N/mm respectively.

Only the values at \(x = \pm 1850 \text{ mm}\) show a significant deviation. The numerically calculated points show a displacement of 0.1 mm whereas the measured values show no displacement. This is because these points are the supports of the measuring frame on the base plate which makes them the reference points for all other measured values. All measured displacements are relative to the measuring frame and to the supports on which the frame is mounted on. Since the supports are not on the edge of the bolster, but shifted towards the middle of the bolster, the four supports and along with the whole measuring frame is displaced when the bolster bends under load.

The measured displacements therefore do not represent the absolute deflection of the bolster but the displacement relative to the measuring frame. Figure 5 illustrates the displacement of the measuring frame schematically. The curve shows a possible deflection curve. The vertical dotted lines enclose the range that can be measured by the PFP-tool. Within this range the measurement is clearly defined. On the other hand, the dotted line outside the range is not known because it cannot be measured with the PFP-tool.

![Figure 5. Schematic displacement of the measuring frame of the PFP-tool.](image)

To validate the developed substitute model, the data of a second measuring system which is utilized for the approval of forming presses on delivery is used. The system uses a measuring frame where the supports are positioned on the outer corners of the bolster. The deflection can be measured in the front, back and in the middle area of the bolster. This installation is comparable to the measuring areas of the PFP-tool. The measured displacements are almost absolute because the supports are so close to the corners that they are nearly static.

The force with this measuring system is applied by four pillars with built-in oil pressure cylinders which are positioned in a rectangular formation in the middle of the bolster. In contrast to the PFP-tool, the measurement in this measuring system is static.

For validation, the substitute model of the bolster with the optimized parameters that were determined previously is used. The four pillars of the measuring system are positioned on the substitute model just as in the experiment. The load of 10,000 kN is applied via pressure on the pillars. The resulting calculated deflection curves with the measured values are shown in Figure 6. The numerically determined displacements are consistently lower than the measured values with a mean squared error of 0.00247. This indicates that the optimized substitute model has a high stiffness. This finding supports the earlier established conclusion on the displacement of the measuring frame. This means that the measured displacements from the tactile sensors of the PFP-tool cannot be used as
target figures for the optimization of the substitute model without further adjustments. The analysis of the difference between measured and numerically calculated displacements leads to an assumed displacement of the measuring frame to be 15% of the maximally measured displacement in the middle of the bolster.

Figure 6. Comparison between numerically calculated displacements of the substitute model based on the original PFP-tool measurement data and absolute measured values of the measuring system used for the approval of presses at a total load of 10 000 kN.

Based on these findings the measured results from the PFP-tool are adjusted for a new set of optimized parameters for the substitute model. The assumed displacement of the measuring frame with 15% of the maximum measured displacement in the middle of the bolster is added to all measured displacements. The optimization of the new substitute model is done as described above. The adjusted measurement values and the numerically calculated displacements from the new substitute model are shown in Figure 7.

Figure 7. Optimization result based on adjusted measuring results of the PFP-tool at 10 000 kN.
It is noticeable that the supports of the measuring frame at $x = \pm 1850$ mm now show a displacement due to the adjustment. Due to this adjustment the numerically calculated values are significantly closer to the measured values. The mean squared error is at 0.000273 and thus clearly smaller than the error in the first substitute model. As expected, the optimized spring constants and the elastic modulus are smaller compared to the first model due to the larger prescribed target figures. The elastic modulus is 163 000 N/mm² and the spring constants of the long and short assemblies are 2 178 000 N/mm and 3 000 000 N/mm respectively.

The new substitute model is also validated by means of the secondary measuring system as described above. The result of the validation is depicted in Figure 8. For the measurements in the front and back of the bolster, the numerically calculated displacements are almost congruent to the measured values. However the points at the measuring bar in the middle of the bolster show a deviation of about 0.05 mm on average. In contrast to the validation of the first substitute model in Figure 6, the numerically calculated curve depicted in dotted lines shows a higher displacement compared to the measured values. This means that the substitute model does not have sufficient stiffness to accurately reproduce the expected behaviour for the applied load in the middle of the bolster.

One possible explanation for the deviation could be the differences in the load application between PFP-tool and the validation measuring system. The substitute model is optimized for an extensive load application as it occurs with the PFP-tool measurement as well as with real production tools. In contrast to this, the validation measurement system applies the load centred in the middle of the bolster which leads to a deviation in the system response. Further, the correction factor of 15% could be quite high resulting in a substitute model without sufficient stiffness.

Compared to the first substitute model, the mean square error for the new model is smaller at 0.000618 and so the adjustment of the PFP-tool measurement data increases the accuracy of the substitute model overall.

![Figure 8](image_url)

**Figure 8.** Comparison between numerically calculated displacements of the substitute model based on the adjusted PFP-tool measurement data and absolute measured values of the measuring system used for the approval of presses at a total load of 10 000 kN.

5. Conclusion
The developed substitute model is able to replicate the deflection behaviour of the bolster of the examined press A with high accuracy. To evaluate the robustness of the model, examinations on
additional presses are necessary. Especially bolsters with special constructive features like extra fortifications have to be verified.

For the examined press A, the displacement of the PFP-tool measuring frame can be compensated with a correction factor of 15% applied to the maximal measured deflection in the middle of the table. To successfully apply this method on any desired press, the displacement of the frame has to be examined further. With a variety of extrapolation approaches, the expected deflection course in the area outside the measuring frame can be determined approximately. It is topic of further research to devise a universal approach that provides sufficiently accurate results. It would be preferred to extend the PFP-tool to measure the displacements of all four supports of the measuring frame relative to the corners of the bolster routinely to have fixed boundary conditions for the optimization.

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