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Stiffness of multipoint servo presses: Mechanics vs. control

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ABSTRACT

The accuracy of metal-formed products is strongly affected by the stiffness of the machine used. Therefore, huge efforts to increase moments of inertia and reduce backlash were made in conventional press design. Multipoint servo presses allow for an alternative approach: increasing the position accuracy with respect to the press stroke direction and the ram tilting by controlling deflections. Necessary models and parameters as well as the effectiveness of such a control are discussed in this paper. The proposed method is validated by experiments using a 3D servo press.

1. Introduction

Presses actuate tools along predefined paths. As they are heavily loaded, accurate positioning is challenging. Inaccuracies can cause dimensional deviations from the required product geometry or tool damage. Possible reasons for the inaccuracies are varying conditions of the press or the tools as well as load variations caused by fluctuating process conditions, e.g., temperature, material, and lubrication. Due to the elastic behavior of the press components, varying loads lead to different deflections of the press. High stiffness values are desirable, since they reduce deviations from the targeted tool paths. Therefore, stiffness is one of the most important characteristics of presses [1]. High values should guarantee ram parallelism and accurate tool guidance.

Two approaches are commonly known to influence the stiffness of presses. These are the adaption of the mechanical press design on the one hand [2], and the active compensation of the ram deflections using a closed-loop control on the other hand. Different frame and gear drive designs vary with respect to the achievable press stiffness [1]. One important design restriction in the optimization of the mechanical press stiffness is the necessary accessibility of the working space [3].

Increasing stiffness by control requires active components and methods for stiffness identification. So far, measurements of press stiffness focus on the stroke direction and the rotational stiffness around the horizontal axes of the ram [4]. Although complete 6 by 6 compliance matrices have already been identified in experiments for both hydraulic [5] and mechanical [6] presses, only single operation points of a press have been considered. This follows DIN 55189 [4], which suggests that the compliance has to be measured at the bottom dead center. Numerical press models, e.g., finite element models, are often used in press design to evaluate the press behavior, but can only be used offline due to their high computing time. Even though reduced order models are required for control, their effectiveness for the stiffness determination has still to be examined.

The possibility to control the ram position and thus to influence the stiffness of the press has been enabled by servo presses through a feedback of the slide positions [7]. Servo presses feature an adjustable bottom dead center. Therefore, position-dependent values of the press compliance are necessary for a position control. Since a direct measurement of the ram position is often impracticable during forming processes, an observer might be required. In case of using a single point servo press, only the stiffness in stroke direction can be controlled. For multipoint servo presses with several independent drive systems, the tilting of the ram can also be manipulated, thus boosting the rotational stiffness. Due to the risk of press damage, ram tilting has to be compensated in conventional spindle-driven multipoint servo presses with respect to the guidance. Contrary to this, the 3D Servo Press [8] shown in Fig. 1 is equipped with special linkage mechanisms and ram bearings resulting in two additional degrees of freedom in the ram movement. Thus, this press type is less sensitive to ram tilting and position control is not limited by the ram bearings. Assuming the press stiffness to be controllable corresponding to the driven degrees of freedom of the ram, the effect of a closed-loop control on the stiffness values is of high interest.

In the present study, the compliance of the 3D Servo Press is determined for different operation points. In addition, a complete 6 by 6 compliance matrix is evaluated with and without position control of the ram. The effect of control, measurement position and the usage of adequate observers will be compared by means of the measured compliance matrices. With that, the coupling behavior between the controlled and uncontrolled 3D Servo Press is investigated and the dependency between the linking mechanism's position of the 3D Servo Press and its stiffness is shown.

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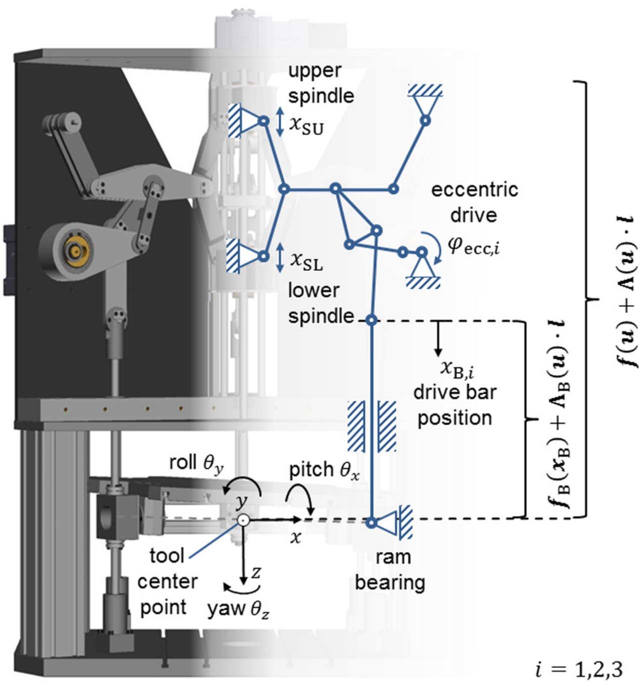

Fig. 1. Linkage mechanism of the 3D Servo Press.

2. Mechanics

In the following, the press used for the investigations as well as the compliance model and test setup will be explained.

2.1. 3D Servo Press

Multipoint servo presses driven by multiple servo motors can perform an asynchronous movement. The 3D Servo Press has three independent drive systems and special bearings, which allow intentional tilting up to 3° in θ_x and θ_y.

As shown in Fig. 1, three eccentric drives in a 120° arrangement and two spindle motors allow for a combined actuation of the ram. Besides three spatial degrees of freedom at the ram z, θ_x, θ_y (stroke, pitch, roll), adjustable mounting height and stroke length are provided. To control the ram position, the eccentric drives $\varphi_{ecc,i}$ as well as the upper spindle x_{SU} and lower spindle x_{SL} work together simultaneously. Therefore, the press system can be described by the drive positions as press input $\boldsymbol{u}$, the ram positions $\boldsymbol{x}$ as press output

$$\boldsymbol{x} = \begin{bmatrix} x \\ y \\ z \\ \theta_x \\ \theta_y \\ \theta_z \end{bmatrix}, \boldsymbol{u} = \begin{bmatrix} \varphi_{ecc,1} \\ \varphi_{ecc,2} \\ \varphi_{ecc,3} \\ x_{SU} \\ x_{SL} \end{bmatrix}.$$

and the kinematic transfer function $\boldsymbol{f}(\boldsymbol{u})$ [9], which represents the kinematic model. It has to be noted that the drive system allows for ram movements with a bottom dead center not coinciding with the bottom dead centers of all eccentric drives.

Process forces and torsional moments lead to a deflection of the ram and therefore to a deviation from the desired position. These loads can be represented as a load vector $\boldsymbol{l} = [F_x, F_y, F_z, M_x, M_y, M_z]^T$. As stated before, it is suggested that the deflection of the ram position $\Delta\boldsymbol{x}$ depends on the drive positions.

2.2. Compliance model

The compliance of a press can either be determined through measurements or a press model. When evaluating the compliance for different positions of the linkage mechanism, the effort put into measurements increases significantly.

Numerical simulation methods are widely used to evaluate the behavior of presses. In order to obtain the press compliance for all positions $\boldsymbol{u}$, an efficient simulation technique is required. For this purpose, a multibody simulation based on a mixed truss and beam model has been developed for the 3D Servo Press and implemented in Matlab. All bodies of the linkage mechanism have been modeled with their corresponding cross-sectional area, material parameters and geometrical moment of inertia. The connections between the bodies are modeled as frictionless springs whose stiffness values represent their bearing behavior.

As outlined by Chodnikiewicz [6] and Arentoft [10], the press deflection behavior can be described by measuring a 6 by 6 compliance matrix Λ. This matrix describes the dependency between the translational and rotational ram positions $\boldsymbol{x}$ and the process loads $\boldsymbol{l}$ such that $\Delta\boldsymbol{x} = \Lambda\boldsymbol{l}$. Due to the variability of the linkage mechanism of the 3D Servo Press, a nonlinear compliance matrix $\Lambda(\boldsymbol{u})$ is considered. The elements λ_{ij} of the compliance matrix

$$\Lambda(\boldsymbol{u}) = \begin{bmatrix} \lambda_{11} & \lambda_{12} & \lambda_{13} & \lambda_{14} & \lambda_{15} & \lambda_{16} \\ \lambda_{21} & \lambda_{22} & \lambda_{23} & \lambda_{24} & \lambda_{25} & \lambda_{26} \\ \lambda_{31} & \lambda_{32} & \lambda_{33} & \lambda_{34} & \lambda_{35} & \lambda_{36} \\ \lambda_{41} & \lambda_{42} & \lambda_{43} & \lambda_{44} & \lambda_{45} & \lambda_{46} \\ \lambda_{51} & \lambda_{52} & \lambda_{53} & \lambda_{54} & \lambda_{55} & \lambda_{56} \\ \lambda_{61} & \lambda_{62} & \lambda_{63} & \lambda_{64} & \lambda_{65} & \lambda_{66} \end{bmatrix}$$

describe the quantitative influence of the loads on the ram deflection and are significant characteristics of the press accuracy under loaded conditions. For instance, the compliance λ_{33} has to be reduced to increase stiffness in stroke direction. The deflections of the tilting angles are specified by the elements in the fourth and fifth row (λ_{4j}, λ_{5j}), mainly by λ_{44}, λ_{55}. For the stiffest design of presses, all elements have to be as low as possible.

By evaluating the compliance for the operation area, a position-dependent compliance matrix $\Lambda(\boldsymbol{u})$ can be generated. Especially for the mechanical and control design of parallel kinematic machines, such stiffness or compliance models are very helpful to predict the machine's behavior [11]. As the kinematic shown in Fig. 1 has a highly nonlinear transfer function $\boldsymbol{f}(\boldsymbol{u})$, no explicit solution for $\Lambda(\boldsymbol{u})$ can be given. Therefore, the compliance was calculated implicitly for the operation area of the machine. The influence of the upper and lower spindle positions x_{SU}, x_{SL} at constant $\varphi_{ecc,i}$ on the compliance in z direction λ_{33} is presented in Fig. 2. Simulating the compliance matrix at a reference point $\boldsymbol{u}_{ref}$ results in the following values unequal to zero:

$$\lambda_{11} = 0.6\frac{\text{mm}}{\text{kN}}, \lambda_{22} = 1.5\frac{\text{mm}}{\text{kN}}, \lambda_{33} = 1.5\frac{\text{mm}}{\text{kN}}, \lambda_{44} = \lambda_{55} = 1\frac{\circ}{\text{kNm}}, \lambda_{66} = 0.3\frac{\circ}{\text{kNm}}, \lambda_{16} = -0.8\frac{\text{mm}}{\text{kNm}}.$$

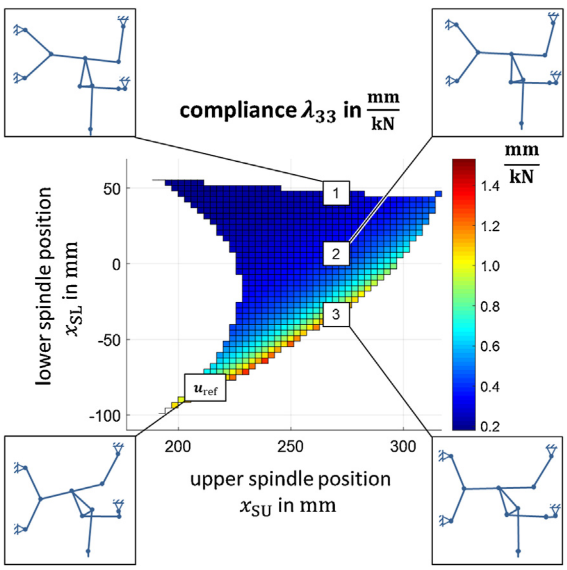

Fig. 2. Simulated compliance map for λ_{33} at constant $\varphi_{ecc,i}$ = 270° over the operation area of x_{SU}, x_{SL}.