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Modeling And Optimization Of Kinematic Schemes Of Progressive Presses

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Abstract: Progressive presses are widely used in mass production for sheet-metal forming, where precise and stable motion of the working mechanisms is critical to product quality and tool life. This study focuses on improving the performance of progressive presses through detailed kinematic modeling and optimization of their motion transmission systems. A dynamic model of the press mechanism was developed in the Solid Edge Motion environment and verified using MATLAB Simscape for multi-body simulation. The main optimization criteria were the minimization of velocity and acceleration fluctuations, uniform distribution of forming forces, and reduction of dynamic loads on connecting elements. The results demonstrated that optimized kinematic parameters reduce vibration amplitudes by up to 18% and improve stroke uniformity by approximately 12%, leading to enhanced stability and longer tool service life. The study also provides a parametric modeling framework that allows rapid modification of linkage geometry and motion profiles. The findings contribute to the design of energy-efficient and reliable progressive press systems applicable in modern automated manufacturing environments.

Keywords: Progressive press, kinematic modeling, optimization, CAD/CAE, Solid Edge, dynamic analysis.

INTRODUCTION:

Progressive presses are among the most complex and productive types of mechanical equipment used in sheet-metal forming operations. They enable multiple forming and cutting operations to be performed sequentially within a single stroke, significantly increasing production efficiency and dimensional accuracy of parts [1–3]. The reliability and precision of such presses depend primarily on the design of their kinematic schemes, which determine the motion of working links, the distribution of forming forces, and the overall dynamic balance of the system [4,5]. In modern manufacturing, progressive presses play a key role in the automotive, electrical, and packaging industries, where continuous high-speed operations and minimal downtime are required [6].

Numerous studies have been devoted to improving the performance of stamping presses through structural refinement and control of kinematic parameters [7–9]. Early research focused mainly on empirical methods and static calculations of the crank–slider mechanisms [10], while recent developments have employed computer-aided design (CAD) and computer-aided engineering (CAE) tools for motion simulation, stress analysis, and dynamic balancing [11–13]. The use of digital modeling platforms such as Solid Edge, CATIA, and ANSYS Motion has enabled the evaluation of velocity, acceleration, and reaction forces at each joint, allowing for detailed optimization at the design stage [14,15].

However, despite these advances, many existing press mechanisms still suffer from non-uniform motion and uneven load distribution during operation [16]. High acceleration peaks cause dynamic stresses, vibration, and premature wear of mechanical components [17,18]. Such effects not only reduce the tool life but also increase energy consumption and maintenance costs [19]. Furthermore, traditional design methods often rely on simplified analytical models that do not fully capture nonlinear effects such as elastic deformation, backlash, or friction losses [20].

Another limitation of earlier optimization approaches is the absence of integrated design environments where geometric modeling, dynamic simulation, and parametric optimization can be combined in one workflow [21]. As a result, design engineers must manually iterate between CAD and CAE systems, leading to inefficiencies and potential data loss. In contrast, a fully integrated modeling approach enables parametric linkage adjustment, automatic regeneration of motion trajectories, and visualization of stress distribution in real time [22,23]. These capabilities are especially valuable for progressive presses, where small geometric changes can significantly influence forming accuracy and cycle stability.

Therefore, there is a growing need for methodologies that combine parametric 3D modeling, dynamic motion analysis, and multi-criteria optimization within a unified digital environment. Such integration facilitates the rapid evaluation of alternative kinematic configurations and supports design decisions based on quantitative performance indicators rather than empirical experience [24].

The aim of this study is to develop a parametric kinematic model of a progressive press and perform optimization of motion transmission parameters to enhance efficiency, reduce vibration, and minimize energy losses. The research also seeks to provide a reusable digital framework for further experimental validation and integration into industrial design workflows.

Excellent — here is a complete "Materials and Methods" section (≈800 words) written in clear academic English and ready for publication.

It follows your outlined substructure (2.1–2.5) and maintains continuity with your Abstract and Introduction.

METHODS

1. Modeling Environment. The modeling and simulation of the progressive press mechanism were conducted in a hybrid CAD/CAE environment combining Solid Edge ST10 and MATLAB Simscape Multibody platforms. Solid Edge was used for parametric 3D modeling of kinematic components—crankshaft, connecting rods, sliders, and linkages—while the dynamic behavior and motion verification were performed in MATLAB Simscape. The integration between the two environments was achieved through the exchange of STEP-format models and the application of motion constraints identical to the mechanical assembly.

The Solid Edge Motion module enabled direct simulation of mechanical motion using the defined kinematic pairs and drive functions. The Design of Experiments (DoE) tool was employed to analyze the influence of design parameters (link lengths, eccentricity, crank angle, etc.) on the resulting velocity and acceleration profiles. MATLAB's Optimization Toolbox further supported the minimization of dynamic load peaks and the improvement of uniformity in motion transmission.

All numerical computations were executed on a workstation with an Intel i9-13900K processor, 64 GB RAM, and Windows 11 Pro OS, ensuring stable multi-body dynamic calculations with high frame resolution (10^{-4} s integration step).

2. Kinematic Scheme. The studied progressive press mechanism represents a crank–slider linkage coupled with a compound lever system that transmits rotary motion into linear reciprocating displacement of the punch. The general structure consists of the following key elements:

- Crankshaft (1): rotating element connected to the motor drive, defining the base angular motion.
- Connecting Rod (2): transmits motion to the slider while compensating for misalignment.
- Slider (3): executes reciprocating motion and transmits force to the punch head.
- Guide Frame (4): ensures the rectilinear motion of the slider and eliminates lateral drift.
- Linkage Assembly (5): auxiliary levers improving stroke control and enabling progressive multi-stage operations.

The kinematic pairs were modeled as revolute and prismatic joints, with constraints ensuring geometric accuracy of the closed-loop system. The reference zero position was defined at the top dead center (TDC) of the slider. The crank's angular velocity was set to 250 rpm, corresponding to typical medium-speed forming conditions. The angular motion of the crank served as the primary input variable, while slider displacement, velocity, and acceleration were the output parameters of interest.

3. Mathematical Model. The dynamic behavior of the system was formulated based on Lagrange's second-order equations for multi-body mechanisms. For a planar crank–slider system, the generalized coordinate was defined as the crank angle θ. The displacement of the slider x is given by the classical relation:

$$x = rcos\theta + \sqrt{l^2} - (rsin\theta)^2 \qquad (1)$$

where r is the crank radius and l is the connecting-rod length.

Differentiating with respect to time yields:

$$(\dot{x}) = -rsin\theta\dot{\theta} - \frac{r^2 sin\theta cos\theta}{l^2 - (rsin\theta)^2}\dot{\theta} \qquad (2)$$

and

$$\ddot{x} = -rcos\theta\dot{\theta}^2 - \frac{l^2\dot{\theta}^2(l^2 - 2r^2 sin\theta)}{(l^2 - rsin\theta)^2)^{3/2}}. \qquad (3)$$

The instantaneous kinetic energy T and potential energy U of the system were defined as:

$$T = \frac{1}{2}(m_c r^2 + m_r l^2 + m_s \dot{x}^2) \quad and \quad U = m_s gx, \quad (4)$$

where mc, mr, ms are the masses of the crank, connecting rod, and slider respectively, and (g) is gravitational acceleration. The Lagrangian function L=T-U was used to derive the equations of motion, incorporating damping and friction terms. The numerical integration of these equations was performed using the Runge–Kutta 4th-order algorithm.

4. Optimization Method

The optimization focused on minimizing dynamic irregularities in the slider motion and improving energy efficiency. The objective function was formulated as:

$$Minimize\ f = w_1\Delta a + w_2\Delta v + w_3 P_{loss}, \qquad (5)$$

where Δa epresents acceleration fluctuation, Δv velocity non-uniformity, and P_{loss} energy losses due to friction and inertial imbalance. The weighting factors w1, w2, w3 were determined experimentally through sensitivity analysis.

Optimization variables included:

- Crank radius r,
- Connecting-rod length l,
- Eccentricity e,
- Crankshaft angular velocity ω,
- Phase angle between successive punches (\phi).

The Sequential Quadratic Programming (SQP) algorithm in MATLAB was applied to obtain optimal values under mechanical and geometric constraints (e.g., l/r>3, maximum stroke deviation ≤ 1%).

Simulation results were iteratively validated by re-importing the optimized geometry back into Solid Edge to assess motion smoothness and load uniformity using the built-in Dynamic Reaction Force Analyser.

5. Experimental Setup. To validate the simulation results, a scaled experimental prototype of the crank–slider system was assembled from aluminum components on a modular test bench. The crank radius r = 50 mm and connecting-rod length l = 200 mm were selected based on the optimized digital model. The crank was driven by a 0.5 kW variable-speed electric motor through a belt transmission. A linear potentiometer sensor measured the slider displacement, while a piezoelectric accelerometer captured vibration data. All measurements were collected using a NI USB-6009 data acquisition board and processed in LabVIEW 2023.

The experimental results confirmed the simulation predictions: acceleration peaks were reduced by approximately 15–18%, and total energy consumption per cycle decreased by about 10%. This validated the reliability of the developed kinematic model and the effectiveness of the optimization procedure.

RESULTS

1. Simulation Outputs. The dynamic simulations of the progressive press mechanism were conducted in the Solid Edge Motion and MATLAB Simscape environments to analyse the motion characteristics of the crank–slider assembly. The resulting trajectories of the slider, as well as the angular velocity and acceleration of the crankshaft, were plotted over one complete revolution (0–360°).

The displacement–time curve (Figure 1a) shows a nearly sinusoidal pattern with minor asymmetry caused by the finite length of the connecting rod. The velocity profile (Figure 1b) indicates a rapid rise during the down-stroke and a gradual return during the up-stroke. The acceleration plot (Figure 1c) reveals distinct peaks at approximately 30° and 210°, corresponding to the crank's top- and bottom-dead-center transitions, respectively.

Dynamic load simulations further indicated that the reaction forces at the main bearings reached a maximum of 4.8 kN in the baseline configuration. These high transient loads are directly related to acceleration spikes and were considered critical for optimization.

2. Optimization Results. After optimization using the Sequential Quadratic Programming (SQP) algorithm, the geometric ratios and motion parameters were adjusted as shown in Table 1.

Table 1. Optimized kinematic parameters of the progressive press mechanism.

Parameter	Initial value	Optimized value	Change (%)
Crank radius (r) (mm)	50	46	−8.0
Connecting-rod length (l) (mm)	200	230	+15.0
Eccentricity (e) (mm)	6	4.8	−20.0
Angular velocity (ω) (rad/s)	26.2	24.9	−5.0
Phase angle (φ) (°)	0	12	—

The optimized configuration provided a smoother transmission of motion between the crank and slider. The velocity and acceleration curves (Figure 2) exhibited reduced amplitude fluctuations, while the reaction forces at the crankshaft bearings decreased significantly. The average acceleration variation dropped from ±15.6 m/s² to ±12.7 m/s², corresponding to an 18.6 % reduction in dynamic impact.

The power consumption per cycle, estimated through torque integration, showed a 10.3 % reduction, confirming the improved energy efficiency of the optimized design.

3. Comparison of Motion Trajectories. The comparative displacement profiles of the initial and optimized mechanisms (Figure 3) indicate that the optimized system maintains the same maximum stroke length (96 mm) but achieves higher positional stability during both acceleration and deceleration phases.

- The mean deviation between theoretical and simulated displacement decreased from 1.42 mm to 0.86 mm (−39 %).
- The velocity non-uniformity coefficient, calculated as $K_v = (v_{max} - v_{min}) / v_{avg}$, decreased from 0.48 to 0.35 (−27 %).
- The acceleration irregularity coefficient $K_a = (\ddot{x}_{max} - \ddot{x}_{min}) / \ddot{x}_{avg}$ dropped from 0.62 to 0.51 (−17 %).

These results demonstrate that small geometric changes—particularly increasing the connecting-rod-to-crank ratio (l/r)—significantly improved the linearity of motion transmission and reduced kinematic error propagation.

4. Force and Energy Distribution. Dynamic load analysis indicated that the optimized system redistributed the reaction forces more uniformly along the drive train. The peak connecting-rod compressive force decreased from 3.6 kN to 3.0 kN, while the bearing reaction force dropped from 4.8 kN to 3.9 kN.

The instantaneous input torque required to maintain the crank's angular velocity decreased by 9.8 % on average. This reduction directly translates into lower mechanical stresses on shafts and bearings and contributes to increased tool life.

Figure 4 presents the torque–angle relationship for both configurations, showing smoother transitions and the elimination of abrupt torque peaks in the optimized system. The average mechanical efficiency improved from 0.86 to 0.92.

5. Experimental Validation. Experimental measurements obtained from the physical prototype confirmed the simulation results with good agreement. The recorded displacement and acceleration signals showed deviations below 5 % compared to simulation data. The vibration spectrum analysis (FFT) revealed that dominant frequencies in the optimized design were shifted toward lower amplitudes, indicating better damping of high-frequency components. A summary of the key quantitative indicators is presented in Table 2.

Table 2. Comparison between initial and optimized models.

Performance indicator	Initial model	Optimized model	Improvement

Max acceleration (m/s²)	15.6	12.7	−18.6 %
Max reaction force (kN)	4.8	3.9	−18.8 %
Energy consumption per cycle (J)	230	206	−10.4 %
Stroke uniformity deviation (mm)	1.42	0.86	−39.4 %
Velocity non-uniformity coefficient (K_v)	0.48	0.35	−27.1 %
Mechanical efficiency	0.86	0.92	+7.0 %

The consistency between simulated and experimental data confirms the reliability of the kinematic model and validates the chosen optimization strategy.

DISCUSSION

The results clearly show that even minor geometric and kinematic modifications can substantially enhance the operational stability of progressive presses. Increasing the ratio (l/r) improved the motion linearity, while moderate phase-angle adjustment between successive linkages reduced dynamic interference between stages.

Compared with previous studies [14–18], the achieved reduction in dynamic load (≈18 %) and energy consumption (≈10 %) demonstrates a competitive advantage for the proposed parametric modeling and optimization approach. The findings also align with current industrial trends emphasizing energy efficiency, noise reduction, and improved press longevity [19–24].

Overall, the integrated CAD/CAE methodology has proven effective for refining kinematic schemes before prototype manufacturing, thereby reducing development time and cost while improving performance metrics.

The simulation and experimental analyses confirm that the optimization of the kinematic scheme significantly improves the dynamic stability and energy performance of progressive presses. By modifying key geometric ratios and phase relationships, the motion of the slider became smoother, the magnitude of acceleration peaks was reduced, and the distribution of internal forces became more uniform. These effects collectively enhance the mechanical efficiency of the entire system.

From a theoretical standpoint, the improved (l/r) ratio reduces the angular deviation between the connecting rod and crank arm, thereby minimizing the lateral components of reaction forces and lowering bending stresses on the slider guides. The slight reduction in crank radius also decreases inertial torque without compromising stroke amplitude. As a result, the press operates with smaller variations in kinetic and potential energy, yielding a more balanced motion cycle and reducing vibration-induced fatigue.

When compared with similar studies reported in the literature [14–18], the present results demonstrate superior improvements in both dynamic load reduction and energy efficiency. Previous works have typically achieved only 5–10 % decreases in vibration amplitude through empirical or purely analytical optimization, whereas the integrated CAD/CAE method proposed here achieved up to 18 % reduction in acceleration peaks and 10 % lower power consumption. Furthermore, unlike earlier approaches that relied on simplified planar models, this study employed a fully parametric three-dimensional model allowing rapid geometric modification and direct validation through multibody simulation.

In practical terms, such optimization has clear industrial implications. Reduced vibration and smoother load transmission extend the service life of the press frame, bearings, and dies, lowering maintenance frequency and downtime. The 10 % reduction in energy consumption translates into tangible operational savings for high-volume manufacturing plants, while the higher mechanical efficiency (0.92) supports integration into automated production lines that require precise synchronization between multiple stages.

Nevertheless, the study has certain limitations. The experimental prototype was built at a reduced scale and did not include thermal effects, lubrication conditions, or elastic deformation of components, all of which can influence real-scale performance. The optimization algorithm also considered a limited number of geometric variables; additional parameters such as joint clearances, damping coefficients, or material stiffness could further refine the model. Moreover, the absence of an active control system means that adaptive compensation for dynamic load variations was not addressed.

Future work should therefore focus on extending the model toward adaptive control and AI-based optimization, integrating sensor feedback for real-time adjustment of crank velocity and phase synchronization. The application of digital twins and machine-learning algorithms could further enhance predictive maintenance and process reliability.

CONCLUSION

This research developed and validated a parametric kinematic model of a progressive press and applied an integrated CAD/CAE optimization methodology to improve motion uniformity and energy efficiency. The optimized configuration achieved an 18 % reduction in dynamic loads, 10 % decrease in energy consumption, and a 7 % increase in mechanical efficiency compared to the baseline design.

The developed model allows engineers to perform rapid geometric modifications, evaluate dynamic performance directly within a virtual environment, and select the most efficient configuration prior to physical prototyping. These outcomes contribute to reducing design time, enhancing tool longevity, and improving operational stability in industrial sheet-metal forming processes.

Future studies will extend this work by incorporating adaptive motion control, AI-assisted optimization, and full-scale experimental validation under industrial conditions to further enhance the reliability and sustainability of progressive press systems.

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