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Design and Analysis of a Planetary Geared Five-Bar Slider Mechanism for Generating Long Dwell Periods

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Abstract: Mechanisms designed for repeated operations are widely used in the processing industry, where the output link undergoes a dwell period when the input link constantly moving. A planetary geared five-bar slider mechanism (PGFBSM) generating stroke-time curves with a long dwell has been proposed. The mechanism consists of a planetary gear train with a slider-crank mechanism. Vector loop equations are utilized for synthesizing the PGFBSM for function generation tasks. By varying each PGFBSM parameter while keeping the other parameters constant, a sensitivity study was conducted. The motion curves were plotted and thoroughly examined to identify the variables that significantly impact dwell generation. The kinematic properties of the PGFBSM evaluated analytically are validated by matching the results with those obtained from SOLIDWORKS simulations. The analytical results closely match the simulation results, valid the results and confirm the accuracy of the proposed model. The results demonstrate the ability of the PGFBSM to produce a three-ram press with a 140° long output dwell, a unique feature not found in conventional presses, which can be tailored for specific applications.

Keywords: Kinematic analysis, Mechanism design, Motion simulation, Synthesis, Slider mechanism

Introduction

A press is a versatile machine tool commonly utilized in mass production of various manufacturing processes. However, certain forming operations, such as drawing and coining and squeezing, require specific slide motion characteristics, such as a long dwell period at bottom dead center. The knuckle joint press mechanism, illustrated in Figure 1, is a widely used press mechanism, consisting of a four-bar with a sliding output (Yelich & Bilur, 2012). The motion of crank is transmitted through a knuckle joint to the slide. The stroke-time curve can be changed by adding a joint. The result is called a modified knuckle joint or toggle drive (The Library of Manufacturing, 2025).

Function generation synthesis is a technique used to design a mechanism that generates an input/output relationship, allowing the input and output to approximate the desired relationship (Copeland & Hayes, 2022; Soylemez & Kipe 2023; Copeland, 2024). The mechanism synthesized in this way is known as a function generator. Function generating mechanisms are utilized in mechanical presses to tackle long-dwell design issues

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in metal forming applications. The dwell period is the period during which the press remains stationary to ensure proper forming or material stamping.

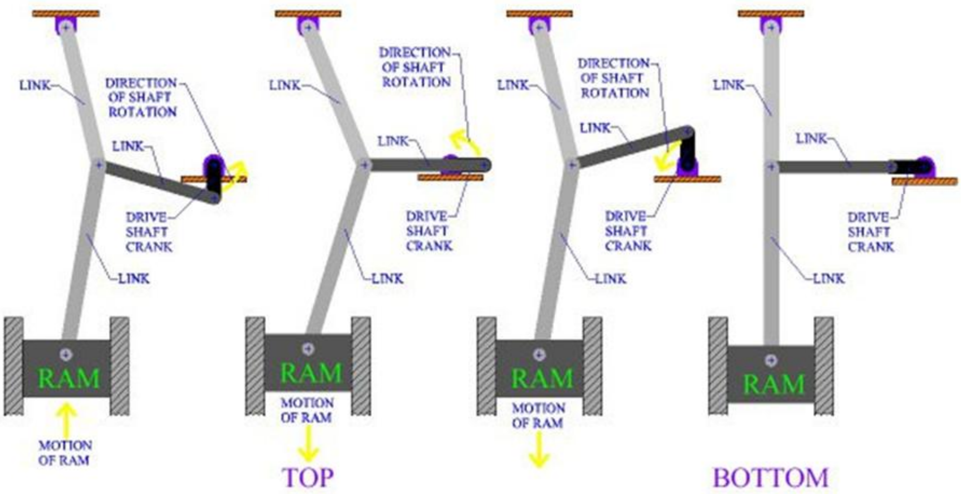


Figure 1. A knuckle joint press (The library of manufacturing, 2025).

The linkage mechanisms constitute the basic structures of mechanical presses. Depending on the DOF of the mechanism used, it is driven by a single-driven (as in the present study) or hybrid-driven (Li & Tso, 2008; Li & Zhang, 2010a, 2010b; Soong, 2012). Numerous studies have been conducted on single-driven presses, focusing on their kinematic performance and the task to be accomplished using various linkages and drive systems. One method is by using different types of mechanisms, such as gear mechanisms (Doege, & Hindersmann, 1997; Soong, et al., 2008). Another method is to combine mechanisms with cams (Mundo et al., 2006). The third method is to vary the length of the link (Soong, 2010, 2016). Lastly, by making the input speed variable (Soong, 2008). However, linkages cannot generate error-free arbitrary functions due to limitations in precision points that can be achieved (Ehyaei, 2024; van der Wijk, 2024). A four-link mechanism can achieve at most five precision points, with structural error being a certainty for more than five points (Ali et al., 2017; Hernández et al.,2021).

To eliminate structural error and achieve accuracy of over five precision points, researchers have introduced adjustable mechanical parts (McGovern, & Sandor, 1973; Naik, & Amarnath, 1989; Soong, & Chang, 2011; Xu, et al, 2024) or by increasing the link numbers of a mechanism, which increases the number of parameters required for mechanism design. To increase the design parameters, gears can be used as part of mechanisms, particularly five-bar mechanisms, for use in generating functions. These mechanisms have been extensively studied for their versatility in many applications, making them a valuable addition to any mechanism (Freudenstein, & Primrose, 1963; Primrose, & Freudenstein, 1963; Oleksa, & Tesar, 1971; Erdman, & Sandor, 1971; Sultan, & Kalim, 2011).

Optimization studies have been conducted to enhance the performance of multi-bar mechanisms (Kang, Y.-H., Lin & You, 2022; Kutuk & Dulger 2022). Mundo, et al. (2009) utilized an optimization technique to achieve a desired path using non-circular gears as part of a five-bar linkage mechanism. Huang et al. (2011) used a genetic algorithm to optimize the link lengths of a five-bar mechanism for clamping applications. Sultan and Kalim (2011) employed optimization techniques to fine-tune the design parameters of geared five-bar slider mechanisms (GFBSMs) to meet specific performance standards. The use of numerical methods and kinematic synthesis allows for the development of mechanisms tailored to particular applications, achieving the required dwell characteristics and motion constraints. Ali et al. (2017) proposed a technique based on incorporating numerous four-bar mechanisms into slider crank and GFPS mechanisms to reduce structural error in function generation mechanisms and achieve wide-range input-output relationships, which may involve long dwell time. Song (2016) introduced a planetary geared linkage mechanism with slider for mechanical presses to produce prolonged dwell. The press features a variable-length crank, demonstrating its superior dwell periods compared to traditional knuckle joint mechanisms. Song et al. (2008) proposed a geared mechanism consisting of a servomotor-driven five-bar linkage and a slider connected by a floating link. This mechanism is suitable for forming machines with constant speed and a long dwell time. Tso and Liang (2002) suggested a linkage mechanism for presses to achieve slow operating speed and ensuring a long dwell period in the dead center. Myszka et al. (2019) explored the utilization of geared five-bar mechanisms with sliding outputs in presses, highlighting their ability to produce longer dwell times compared to traditional knuckle joint mechanisms. This extended dwell is advantageous in operations like coining and squeezing, where prolonged application of force is necessary. While the focus of Myszka et al. (2019) work was on optimizing the slider motion of a geared five-bar mechanisms with sliding outputs and highlighting their ability to produce longer dwell times, the focus of this paper is on developing closed-form relationships to synthesize a planetary geared-slider mechanism that produces a long dwell motion with the required tolerance.

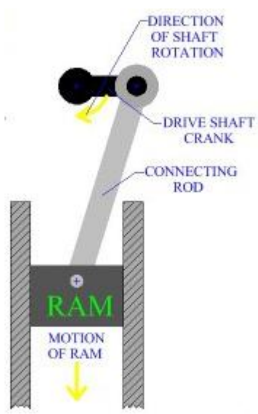
The study aims to create a mechanism with only five links, achieving high dwell accuracy and low error, thereby addressing a major gap in scientific literature by creating a simple mechanism that generates long dwells. The study aims to design a new mechanism using linkages and planetary gears that is capable of generating three equal dwells at 120-degree intervals throughout a complete rotation cycle, while maintaining the structural error within acceptable limits. Specifically aiming for a deviation between the desired and actual dwell lengths of less than 1 % of the stroke. Kinematic analysis using the vector loop method is used to ensure the required dwell time is achieved within the design constraints. The motion of the mechanism is also modeled and simulated to verify the working principle and the accuracy of the mathematical analysis.

Method

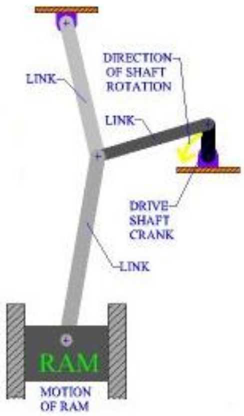
The solution to the problem has been achieved in three phases:

1. Synthesis and analysis of the PGFBSM to obtain the design parameters as proportional quantities for an approximated dwell.
2. Fine-tune the PGFBSM design parameters to ensure the mechanism satisfies specified performance requirements.
3. Determining the PGFBSM design parameters that minimize the deviation of the dwell in the time-displacement curve from a straight line (dwell error). Motion is viewed as a dwell if its amplitude is below a specified tolerance. The objective is to obtain a PGFBSM with minimum deviation below the specified tolerance.

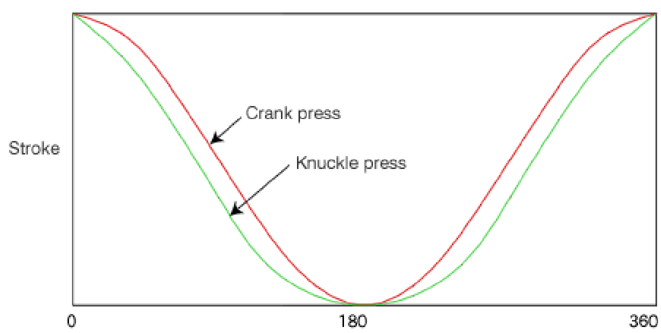
By varying each PGFBSM parameter while keeping the other parameters constant, a sensitivity study was conducted. The motion curves were plotted and thoroughly examined to identify the variables that significantly impact dwell generation. Kinematic characteristics of the PGFBSM evaluated analytically and verified using SOLID WORKS simulation. The simulation results and the analytical results were compared with each other.
The design of repeated operation mechanisms relies heavily on the stroke time curve, illustrated in Figure 2 for a mechanical crank and knuckle joint presses.



(a) A mechanical crank press.



(b) Knuckle joint press.



(c) Stroke time curves.

Figure 2. Stroke time curves of crank and knuckle presses (The Library of Manufacturing, 2025).

Dwell accuracy: The dwell accuracy can be indirectly estimated by measuring the structural error, but the structural error may not accurately express the dwell accuracy due to the possible zero structural error value and the possible difference between the required function and the resulting function. In the PGFBS mechanism, the dwell accuracy can be measured by the deviation of the time-displacement curve of the slider from a straight line (δ, as shown in Figure 3). The maximum permissible deviation (δ_{max}) serves as a tolerance for estimating output link stillness during dwell.

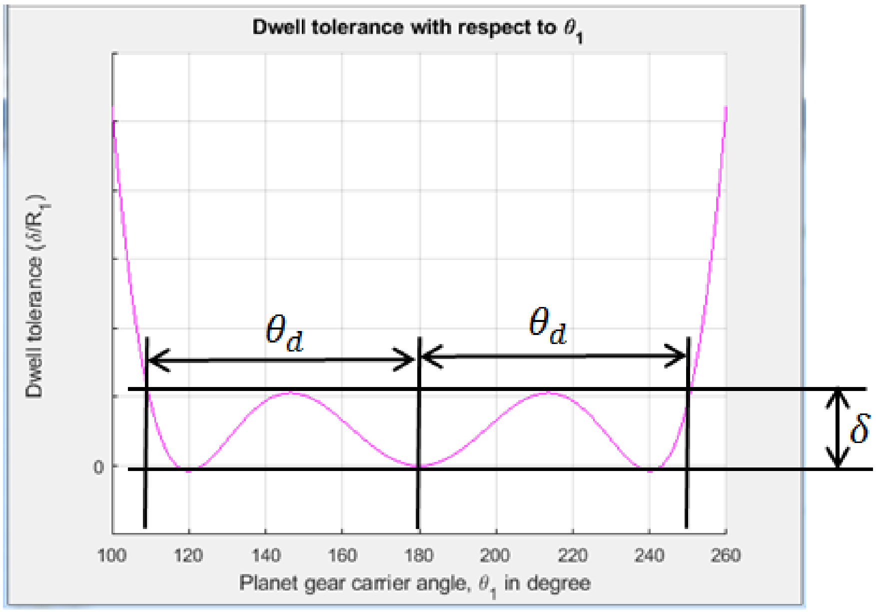


Figure 3. The deviation (δ) of the slider curve from a straight line for a dwell of length $2\theta_d$ and tolerance δ_{max}.

Position of dwell: In many curves that can be generated by PGFBSM, the relative position is chosen so that it provides a stop at the top or bottom dead centers. Since the movement of the output slider is dependent on the movement of the input carrier, accurate measurement of the dwell amplitude can be achieved by measuring the angular range corresponding to the input carrier (Peon-Escalante, et al., 2020).

Width of dwell: The deviation is assessed for a stop period of length $2\theta_d$ and tolerance of δ_{max}, starting from $\theta_1 = 180 - \theta_d$ and ending at $\theta_1 = 180 + \theta_d$.

Stroke ratio: The stroke length (S) is the distance the output slider moves between the top and bottom dead centers. The stroke length must be proportional to mechanism-size ratio, requiring a large mechanism size for a large output stroke and vice versa. The stroke length is measured using the stroke ratio R_{stroke} relative to the PGFBSM dimensions.

$$R_{stroke} = \frac{S - L_{short}}{L_{long} - L_{short}} \tag{1}$$

Where L_{short} and L_{long} are the short and long links in the PGFBSM.
Thus,

$$R_{stroke} = \begin{bmatrix} 0 & \quad when\ S = L_{short} \\ 1 & \quad when\ S = L_{long} \end{bmatrix}$$

To ensure a good proportion ratio, the optimal value of R_{stroke} should be within an acceptable range of 0 to 1.

Kinematic Analysis

Displacement Equation of Planetary Geared Five-Bar Mechanism

Figure 4 shows a schematic drawing of the PGFBSM.

The vector loop required for analyzing PGFBSM is:

$$\overrightarrow{R_1} + \overrightarrow{R_2} - \overrightarrow{R_3} - \overrightarrow{R_4} = 0 \tag{2}$$

Equation (2) can be transformed into

$$R_1 e^{j\theta_1} + R_2 e^{j\theta_2} - R_3 e^{j\theta_3} - R_4 e^{j\theta_4} = 0 \tag{3}$$

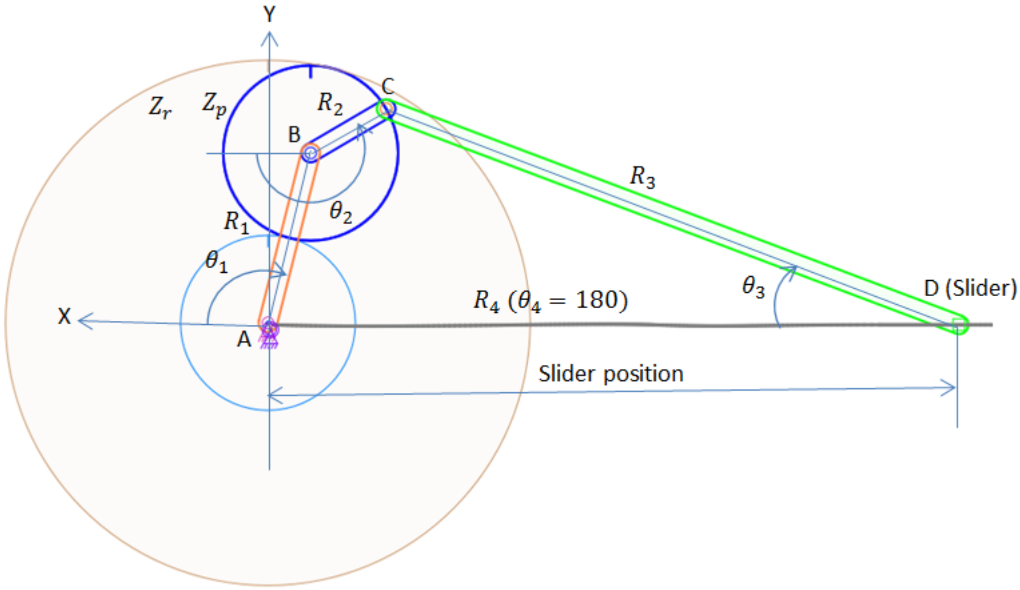


Figure 4. A schematic drawing of the PGFBSM.

The variable θ_1 is the independent variable, while θ_2, and θ_3 are the dependent variables. The coordinate system, set parallel and perpendicular to the slider block axis, results in an angle θ_4 to be180°. The gears are interconnected in their movement, resulting in links 1 and 2 having a specific relationship.

$$\theta_2 = \left(1 - \frac{Z_r}{Z_p}\right)\theta_1 \tag{4}$$

where Z_r, and Z_p are the teeth numbers of planet and ring gears, respectively. Let $\beta = 1 - \alpha$, and

$$\alpha = \frac{Z_r}{Z_p} \tag{5}$$

Then Equation (3) can be written as:

$$R_1 e^{j\theta_1} + R_2 e^{j\beta\theta_1} - R_3 e^{j\theta_3} - R_4 e^{j\theta_4} = 0 \tag{6}$$

Equation (6) can be solved by substituting the Euler equivalents and separating it into its real and imaginary parts.

$$R_1 \cos\theta_1 + R_2 \cos(\beta\theta_1) - R_3 \cos\theta_3 - R_4 \cos\theta_4 = 0 \tag{7}$$

$$R_1 \sin\theta_1 + R_2 \sin(\beta\theta_1) - R_3 \sin\theta_3 - R_4 \sin\theta_4 = 0 \tag{8}$$

For $\theta_4 = 180°$, we get:

$$\cos\theta_1 + \frac{R_2}{R_1}\cos(\beta\theta_1) - \frac{R_3}{R_1}\cos\theta_3 + \frac{R_4}{R_1} = 0 \tag{9}$$

$$\sin\theta_1 + \frac{R_2}{R_1}\sin(\beta\theta_1) - \frac{R_3}{R_1}\sin\theta_3 = 0 \tag{10}$$

Velocity Equation of Planetary Geared Five-Bar Mechanism

By taking the time derivative of Equation (5), the velocity analysis can be obtained, taking into account that the link R_4 varies with time.

$$R_1 j\omega_1 e^{j\theta_1} + R_2 j\beta\omega_1 e^{j\beta\theta_1} - R_3 j\omega_3 e^{j\theta_3} - \dot{R}_4 e^{j\theta_4} = 0 \tag{11}$$

Equation (11) can be solved to find ω_3 and $\dot{R}_4$ as follows

$$\omega_3 = \left[\frac{R_1 \cos\theta_1 + \beta R_2 \cos(\beta\theta_1)}{R_3 \cos\theta_3}\right]\omega_1 \tag{12}$$

$$\dot{R}_4 = \left[\omega_1 \sin\theta_1 + \beta\frac{R_2}{R_1}\omega_1 \sin(\beta\theta_1) - \frac{R_3}{R_1}\omega_3 \sin\theta_3\right]R_1 \tag{13}$$

Acceleration Equation of Planetary Geared Five-Bar Mechanism

Differentiate Equation (11) with respect to time to obtain an expression for the acceleration.

$$R_1 j\omega_1 e^{j\theta_1} + \beta R_2 j\omega_1 e^{j(\beta\theta_1)} - R_3 j\omega_3 e^{j\theta_3} - \dot{R}_4 = 0 \tag{14}$$

Equation (14) can be solved to find α_3 and $\ddot{R}_4$ as follows

$$\alpha_3 = \frac{R_1\alpha_1 \cos\theta_1 - R_1\omega_1{}^2 \sin\theta_1 + \beta R_2\alpha_1 \cos(\beta\theta_1) + \beta^2 R_2\omega_1{}^2 \sin(\beta\theta_1) + R_3\omega_3{}^2 \sin\theta_3}{R_3 \cos\theta_3} \tag{15}$$

$$\ddot{R}_4\left(\frac{m}{sec^2}\right) = \Big[-\alpha_1 \sin\theta_1 - \omega_1{}^2 \cos\theta_1 - \beta\frac{R_2}{R_1}\alpha_1 \sin(\beta\theta_1) + \beta^2\frac{R_2}{R_1}\omega_1{}^2 \cos(\beta\theta_1) + \frac{R_3}{R_1}\alpha_3 \sin\theta_3 + \frac{R_3}{R_1}\omega_3{}^2 \cos\theta_3\Big]R_1 \times 10^{-3} \tag{16}$$

Results and Discussion

From Equation (10), we get

$$\theta_3 = \sin^{-1}\frac{\sin\theta_1 + \frac{R_2}{R_1}\sin(\beta\theta_1)}{\frac{R_3}{R_1}} \tag{17}$$

From Equation (9), we get

$$\frac{R_4}{R_1} = \frac{R_3}{R_1}\cos\theta_3 - \cos\theta_1 - \frac{R_2}{R_1}\cos(\beta\theta_1) \tag{18}$$

The stroke length is measured relative to the dimensions of the PGFBSM, as defined in Equations (17) and (18). The basic design parameters R_1, R_2, and R_3 are written as proportional quantities, allowing for the selection of the length R_1 arbitrarily to scale the dimensions of the mechanism at the end of the design process. The length of the input link R_1 can be considered as a scale factor and is taken as 1.

To meet design requirement 1 and 2, α should be an integer number equal to 3 ($\beta = -2$), ensuring links 1 and 2 return to their initial configuration. Therefore, according to Equation (3), $\theta_2 = -2\theta_1$, implying that for one revolution of link 1, link 2 rotates 2 revolutions in the opposite direction. Then

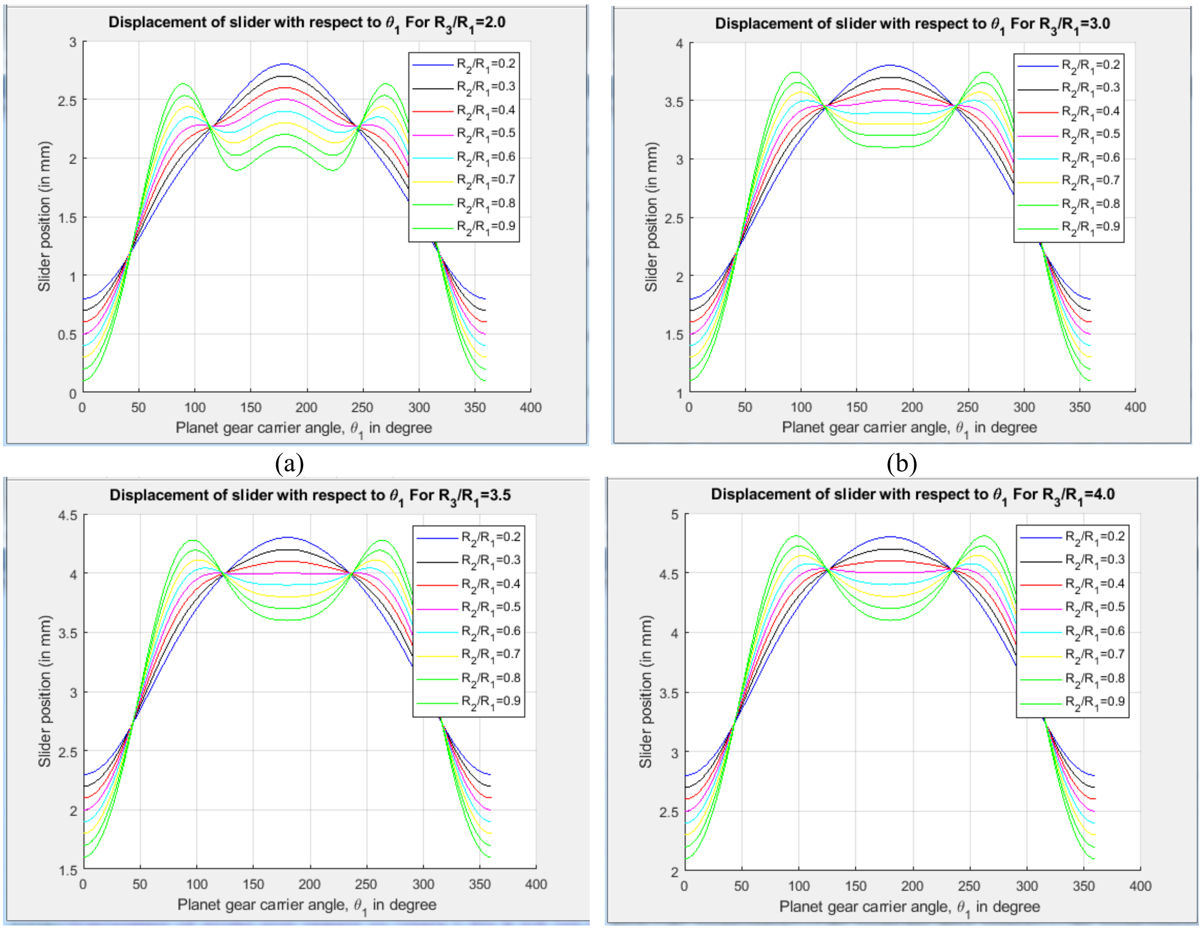
$$\theta_3 = \sin^{-1}\frac{\sin\theta_1 - R_2 \sin(2\theta_1)}{R_3} \tag{19}$$

$$R_4 = R_3 \cos\theta_3 - \cos\theta_1 - R_2 \cos(2\theta_1) \tag{20}$$

A sensitivity study was conducted by varying each parameter of the PGFBSM while maintaining the others parameters unchanged. The motion is analyzed by plotting the linear position R_4 of the output link against the angular position of the input link θ_1. The motion curves generated by these variations were plotted and further studied to identify the parameters influencing the generation of a dwell. Initially the impact of varying link 2 length, R_2 , while maintaining link 3 length, R_3, constant on the generated motion curve is examined.

By taking the length ratio R_2/R_1 as 0.2, the mechanism will produce an approximately sinusoidal reciprocating output motion for all length ratios R_3/R_1. Changing the length ratio R_2/R_1 from 0.3 to 0.5 produces a double oscillation for length ratio $R_3/R_1 = 2$, as shown in Fig. 5 (a), whereas the output curves approach a horizontal or almost horizontal portion for length ratios $R_3/R_1 = 3,\ 3.5$, and 4. For length ratios R_2/R_1 greater than 0.6, a double oscillation is obtained for all length ratio R_3/R_1.

In three of the four cases illustrated, a length ratio R_2/R_1 equals to 0.5 produces an almost horizontal portion of the output curve. The output link is approximately stationary during this period of input rotation, θ_1, from about 100 to 250° as shown in Figs. 5 (b), (c), and (d). These motions are shown by the curves in Figure 6. The output link movement is considered a dwell if its amplitude is less than the specified tolerance.



(a) (b) (c) (d)

Figure 5. The impact of different design parameters on the displacement-time curves, indicating the effectiveness of parameter R_2 & R_3.

To dwell at $\theta_1 = 180°$

$$\theta_3 = \sin^{-1}\frac{\sin 180 - R_2 \sin 360}{R_3} = 0 \tag{21}$$

The required link length R_4

$$R_4 = R_3 \cos 0 - \cos 180 - 0.5 \cos 360 = 3.5 + 1 - 0.5 = 4 \tag{22}$$

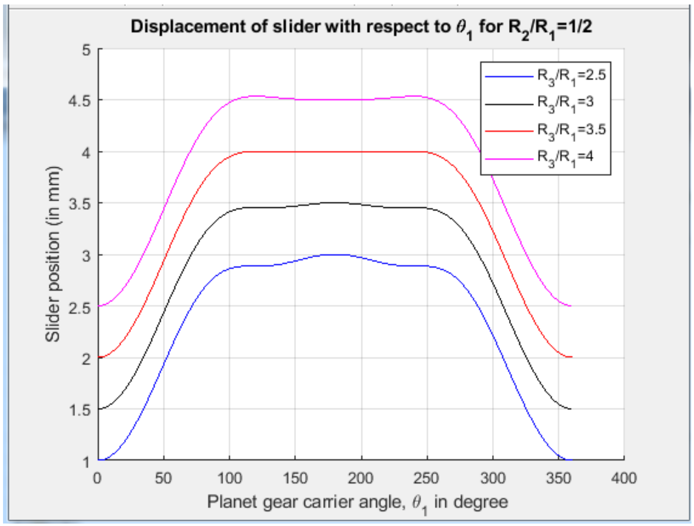


Figure 6. An approximately stationary output curve during the input rotation, θ_1, from about 100 to 250°, indicating the effectiveness of parameter $R_2 = 0.5$.

Design Example

We want to design a mechanism with an output link that can provide a dwell throughout a particular amount of time, from just before to immediately after the forming process, with minimal deviation. The proposed approach is utilized to determine the best dimensions for the proposed mechanism. Let the number of teeth be $Z_r = 45$, and $Z_p = 15$, and let the module be 2. Therefore, the length of the carrier can be calculated to be $R_1 = 60$ mm, while $R_2 = 30$ mm. Substituting these values and the value of $R_3/R_1 = 3.5$ in equation (19); then $R_3 = 210\ mm$. The stroke ratio R_{stroke} relative to the PGFBSM dimensions can be calculated from Equation (1):

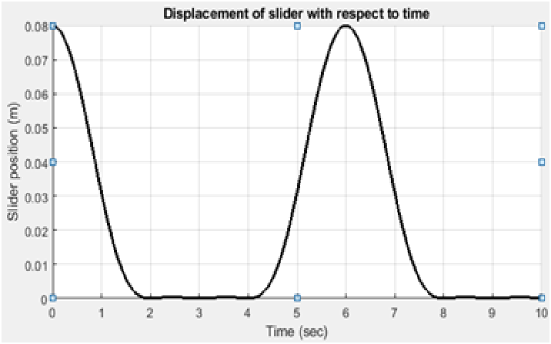
$$R_{stroke} = \frac{S - R_2}{R_3 - R_2} = \frac{80 - 30}{210 - 30} = 0.2778$$

It is within the acceptable range of the stroke ratio.

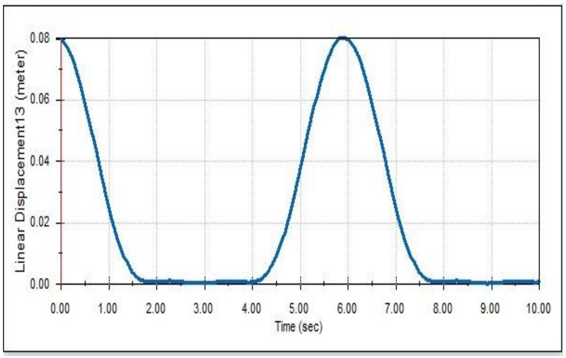
The model of the PGFBSM, shown in Figure 7, is generated by SOLIDWORKS. The input carrier was supposed to have a constant speed of 10 rpm.

Figure 7. Solid model of the proposed design.

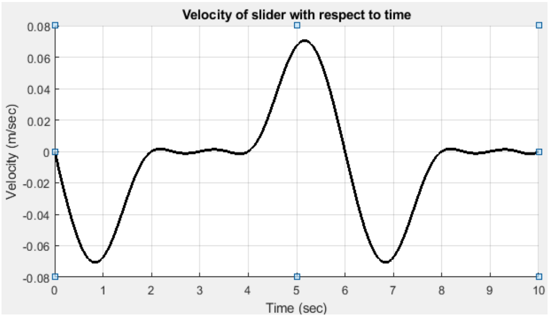
Kinematic simulations are then conducted, and their results are compared to the theoretical results, as shown in Figure 8.



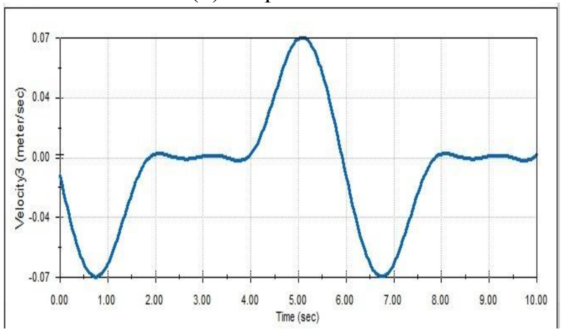
(a) Displacement



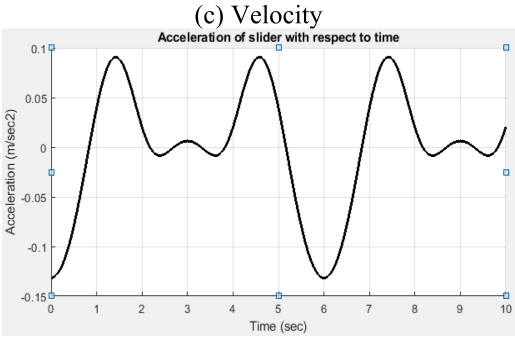
(b) Displacement



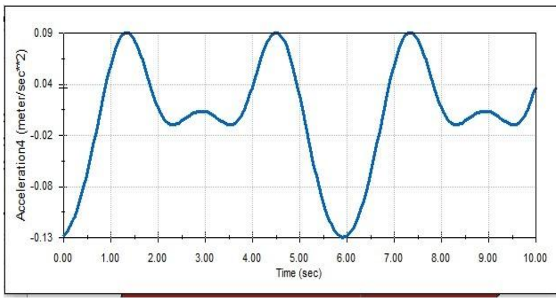
(c) Velocity



(d) Velocity



(e) Acceleration



(f) Acceleration

Figure 8. The slider displacement, velocity, and acceleration, (a), (c), and (e) theoretical results, (b), (d) and (f) SOLIDWORKS simulations.

Figure 8 shows that the kinematic analysis results and the simulation results of the SolidWorks model are identical, which means that the model was created accurately. Figure 8 also indicates that the slider stopped from before to after bottom dead center (BDC) and the rotation angle of the input link varied between $\theta_1 = 110°$ to $\theta_1 = 250°$. Additionally, the figure indicates that the slider moves at approximately constant speed toward BDC. Figure 9 shows the dwell tolerances for a 140° dwell, starting at $\theta_1 = 110°$ and ending at $\theta_1 = 250°$.

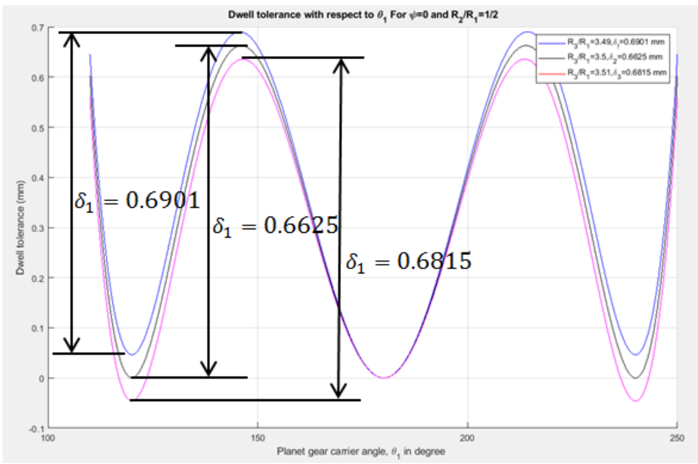


Figure 9. The dwell tolerances for a 140° dwell, starting at $\theta_1 = 110°$ and ending at $\theta_1 = 250°$.

All deviations are less than the tolerance of 1% of the stroke and the best is at $R_3/R_1 = 3.5$. Such dwells are smoother and enough accurate for most applications compared to start-stop mechanisms or Geneva wheels. The proposed mechanism can operate as a three-ram press (a mechanism having three sliders) operating in sequence as shown in Figure 10.

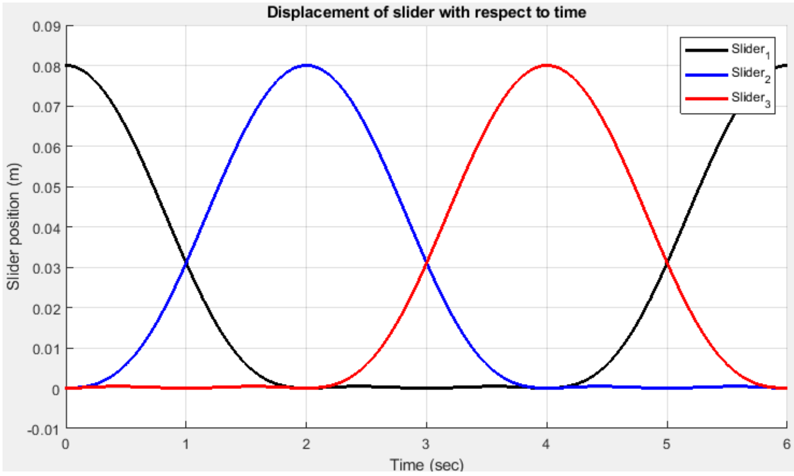


Figure 10. The displacement of the three sliders for a single input link revolution.

Conclusion

This study presented an analytical approach for the design of a planetary geared five-bar slider mechanism (PGFBSM). The PGFBSM simplifies previous methods by requiring only five links and without the need for variable input drivers. The kinematic analysis and synthesis have demonstrated the capability of the single degree mechanism to produce a long dwell (up to 140°) with only minute movement ($<$ 1% of the stroke), thus reducing mechanical complexity. By using a closed-form solution, the proposed method efficiently considers all influential design parameters, allowing easier parameter tuning to meet specific applications. Simulation results obtained from SOLIDWORKS validate the proposed approach and demonstrate its potential as a suitable alternative for mechanisms with long dwells. The significance of this research lies in its ability to enhance productivity in various industries such as manufacturing, food, and paper. Although the analysis results are promising, they have some limitations, including the assumption of ideal conditions, such as perfect joints and zero friction. However, the potential influence of realistic factors, such as material deformation, gear tooth wear, and assembly tolerances, on the actual performance of the mechanism could alter it.

Recommendations

The kinematic analysis and synthesis have demonstrated the suitability of the PGFBSM for various industrial applications, such as processing, packaging, and assembly, where prolonged dwell times are required. Furthermore, the study highlights the potential of parametric sensitivity analysis in the design of mechanisms for specific industrial applications, offering a promising direction for future research and development, eliminating the limitation of precision points. We recommend also using the deviation of the slider time-displacement curve from a straight line using the maximum allowable deviation (δ_{max}) as the tolerance to estimate the output link stillness position instead of the indirect method by measuring the structural error.

Future work should focus on modifying the design parameters and exploring the applicability of the mechanism in specific applications. Also, the slider offset value can be analyzed to maintain a constant speed for a predetermined period before dwell.

Scientific Ethics Declaration

* The authors declare that the scientific ethical and legal responsibility of this article published in EPSTEM journal belongs to the authors.

Conflict of Interest

* The authors declare that they have no conflicts of interest

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