Finite Element Study on Forming Helical Springs by Wire Bending with a Plate

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Abstract. Coil springs, widely used as mechanical elements, will enter another new production outlook due to the application of CNC wire bending machines and as the era of On-Demand Manufacturing is approaching. This article tries to follow the trend and use finite element analysis investigating parameters, such as the angle, shift distance, and wire diameter, applied in a CNC bending machine with a swivel plate as the die on the formed cylindrical helical coil springs. The results show that the angle of the swivel plate normal to the wire feeding direction and shift distance have a significant effect on the spring diameter, while the wire diameter has a significant effect on the spring pitch. The result will be used as a reference for the industry to develop On-Demand Manufacturing machinery applications in the future.

1. Introduction
Spring is an important machine element used to connect other machine elements and to provide them movement along with traction, thrust, or torque by its elastic extension, compression, or torsion incorporated to the dynamically or statically load applied between them. Among the sorts and types of spring used in a machine, helical coil springs have been detailed in tables listed in the machinery handbook [1], from which one can easily pick up according to the assigned working parameters. Furthermore, one can readily design his own helical springs as well according to the mechanical design textbook [2]. This is especially meaningful for the customized market era of Industry 4.0 [3], which has been leading to an On-Demand Manufacturing [4]. To response the potential needs, a CNC wire bending machine [5] has been presenting in the market to provide flexible manufacturing a spring made from a wire coil. Even there is CNC program already built in the machine to create the bending path for manufacturing springs, the instinct springback characteristics of the metal wire after bending is, however, not taken into account in the bending path, so that the made spring geometry might not be the same as desired or designed. If an empirical formula or equation can be specifically provided to compensate the springback after the wire bending, it might help the industry to improve their CNC program manufacturing a perfect spring as desired. This article is thus aimed to investigate the influence of the parameters during wire bending to the final geometry of the formed coil spring. Based on the results provided by this paper, a further study can realize the springback compensation during wire bending for manufacturing customized springs.
2. Setup of experiment and simulation

Using a CNC wire bending machine to form a wire into a helical coil spring, the machine feeds the wire from its mandrel, while a swivel plate in front of the mandrel that can be freely shifted and rotated builds a bending moment between the contact point to the wire and the mandrel tip, so that the portion of the wire, where the bending moment engages, bends to form the needed curvature. The swivel plate furthermore exerts a thrust to the wire to push the wire forming the needed pitch. Figure 1 schematically illustrates the principle to manufacture a helical coil spring with a CNC wire bending machine.

Figure 1. Illustration of the manufacturing process of helical springs by feeding wire and rotating the swivel plate of a CNC wire bending machine.

A wire is fed in Z-direction, while the center of the swivel plate has a given distance \( c \) to the feeding mandrel tip, which has the position of the origin at \( (0, 0, 0) \). The swivel plate has further its own two independent rotation axes, \( X' \) and \( Y' \), on its plane. The swivel plate is first located on the original \( XY \)-plane, the plane nearest to the triad shown in Figure 1, then rotates first around its \( X' \)-axis with an angle \( \alpha \) and followed by rotating around its \( Y' \)-axis with an angle \( \beta \), and thereafter is shifted with a distance \( c \) in the \( Z \)-direction. The declination of the swivel plate is thus defined by the Euler angles to its local \( Y' \)-axis, \( \alpha \), and followed by \( \beta \) to its local \( X' \)-axis. The normal vector \( \vec{n} \) of the swivel plate can be uniquely determined after two times rotation by using matrix manipulation with element rotations as equation (1):

\[
\vec{n} = \begin{bmatrix} \cos \beta & 0 & \sin \beta \\ 0 & 1 & 0 \\ -\sin \beta & 0 & \cos \beta \end{bmatrix} \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos \alpha & -\sin \alpha \\ 0 & \sin \alpha & \cos \alpha \end{bmatrix} \begin{bmatrix} 0 \\ 0 \\ 1 \end{bmatrix}
\]

Or equation (2) after further manipulations:

\[
\vec{n} = \begin{bmatrix} \cos \alpha \sin \beta \\ -\sin \alpha \\ \cos \alpha \cos \beta \end{bmatrix}
\]

The setting parameters of this study for the swivel plate are thus defined by only two Euler angles \( \alpha \) and \( \beta \) for rotation and one shift distance \( c \) for translation.

The commercial finite element software LS-DYNA is applied in this study, which can provide a rigid wall that can efficiently model the swivel plate. The contact between the wire surface to the swivel plate is set as Coulomb friction with a coefficient of 0.125 for usual cold metal forming process, while the contact of the wire surface to itself can be modelled as well. A 65Mn steel having the flow stress \( \sigma = 400.7 e^{0.1428 \varepsilon} \) to its equivalent strain \( \varepsilon \) according to [6] is used to model the wire material. The wire is
200 mm long modelled with the Hughes-Liu cross section integration beam formulation [7] having 16 integration points. To determine the features of a helical coil spring, such as pitch and diameter, after forming, the method used in the industry for determining cylindricity of a shaft is applied [8]. The axis is accordingly calculated and further estimated. Besides the average diameter can be calculated, the average pitch can then be calculated from the individual estimated pitch between two adjacent nodes, in that the estimated pitch is related to their project distance on the spring axis and their sector angle on the \(\pi\)-plane perpendicular to the spring axis. In general, the Hughes-Liu beam effectively generates a constant moment along its length. Thus, meshes need to be reasonably fine to achieve adequate accuracy [9]. However, a finer mesh needs more computation resource. It should be taken a balance between accuracy and efficiency. After verification with several element sizes between 0.05 mm and 1 mm, the element size 0.2 mm is taken for this study. Figure 2 shows the top view and the side view of the formed spring with element size 0.2 mm from its axis.

Figure 2. Top view and side view of the formed spring from its axis.

For finite element model with smaller size, the time step, which is proportional to the element size, is smaller as well. To reduce the solving process time, LS-DYNA allows user to set a larger time step by adding element mass, “mass scaling.” The time step determined by LS-DYNA for the model with element size of 0.2 mm is \(3.42\times10^{-8}\) s. Under this time step, an average diameter in 9.064 mm (standard deviation 0.028 mm) and pitch in 1.018 mm (standard deviation 0.345 mm) are achieved. Compared to the result from the same element size, an average diameter in 9.062 mm (standard deviation 0.030 mm) and pitch in 1.018 mm (standard deviation 0.318 mm), which is obtained under a time step of \(1.08\times10^{-7}\) s, no significant difference can be noticed, but the computer time is 3.16 times shorter by mass scaling. Even the initial and the following mass scaling might cause more kinetic energy, a quasi-static process is ensured in this study because the ratio of the kinetic energy to the internal energy induced by mass scaling is as small as 2% after initial stage.

To further reduce the computation time, the feeding speed of the wire is accelerated directly at the process beginning to the final speed of 500 mm/s within the first 3 mm feeding. Because the acceleration of the wire feeding might cause additional dynamic behavior, such as vibration, the contact point might be changed during the forming process and a non-uniform diameter might be formed. To freeze the unintended vibration, an artificial viscosity is thus implied in the model, in that the mass damping parameter is set as suggested by the software, \(0.4\pi f\), where \(f\) is the lower frequency of the vibration determined from the velocity evolution obtained from the model without an artificial viscosity.

3. Results and Discussion

For a constant angle of the swivel plate normal to the \(Z\)-direction, the influence of different projection angles of the swivel plate to the \(X\)-direction on the formed spring is investigated. Table 1 lists the setups of the swivel plates, whose normal has an angle 45\(^\circ\) to the \(Z\)-direction but different projection angle to the \(X\)-direction, for this investigation and table 2 shows their results on the average pitch and diameter as well as the angle of spring axis to the swivel plate normal. Based on the results obtained by the statistical analysis software IBM SPCC, there is no significant relationship of the results to the projection angle of the swivel plate normal. The standard deviation of the pitch and diameter are 0.007 mm and
0.0128 mm, respectively. Comparing them to the standard industrial tolerance, it can be concluded that there is no significant influence of the projection angle to the pitch or the diameter.

Table 1. Euler angles of the swivel plate having an angle 45° to the Z-direction but different projection angle to the X-direction

| Euler angle (°) | 0   | 10  | 20  | 30  | 40  | 50  | 60  | 70  | 80  | 90  |
|----------------|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|
| α              | 7.05| 14.00| 20.70| 27.03| 32.80| 37.76| 41.64| 44.14| 45  |
| β              | 45  | 44.56| 43.22| 40.89| 37.45| 32.73| 26.57| 18.88| 9.85| 0   |

Table 2. Pitch, diameter, and axis angle obtained with the swivel plate having an angle 45° to the Z-direction but different projection angle to the X-direction

| Projection angle to the X-direction (°) | 0   | 10  | 20  | 30  | 40  | 50  | 60  | 70  | 80  | 90  |
|----------------------------------------|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|
| pitch (mm)                             | 1.018| 1.015| 1.025| 1.012| 1.000| 1.010| 1.018| 1.008| 1.022| 1.019|
| diameter (mm)                          | 8.946| 8.949| 8.932| 8.960| 8.945| 8.960| 8.944| 8.977| 8.945| 8.939|
| axis angle (°)                         | 86.09| 84.90| 86.17| 83.50| 86.27| 83.28| 86.37| 84.26| 86.23| 86.32|

On the other hand, for a constant angle of the swivel plate normal projection angles to the X-direction, here 45°, the influence of angles of the swivel plate normal to the Z-direction on the formed spring is investigated. Table 3 lists the Euler angles of the swivel plates for this investigation and Table 4 shows their results on the average pitch and diameter as well as the angle of spring axis to the swivel plate normal. It can be found further that there is a significant relationship of the diameter and the spring axis angle to the normal angle, while there exists no significant influence of the normal angle on the pitch, which can be interpreted as well under that the standard deviation of the pitch is as small as 0.020 mm. It can be observed that the higher the normal angle of the swivel plate to the Z-direction, the larger the diameter and the larger the spring axis angle to the swivel plate normal.

Table 3. Euler angles of the swivel plate having a normal projection angle 45° to the X-direction but different angle to the Z-direction

| Euler angle (°) | 5   | 10  | 20  | 30  | 40  | 50  | 60  | 70  | 80  | 90  |
|----------------|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|
| α              | 3.53| 7.05| 14.00| 20.70| 27.03| 32.80| 37.76| 41.64| 44.14| -   |
| β              | 3.54| 7.11| 14.43| 22.21| 30.68| 40.12| 50.77| 62.76| 76.00| -   |

Table 4. Pitch, diameter, and axis angle obtained with the swivel plate having a normal projection angle 45° to the X-direction but different angle to the Z-direction

| Projection angle to the X-direction (°) | 5   | 10  | 20  | 30  | 40  | 50  | 60  | 70  | 80  | 90  |
|----------------------------------------|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|
| pitch (mm)                             | 1.009| 1.008| 1.022| 1.016| 1.021| 1.018| 0.990| 1.017| 0.961| -   |
| diameter (mm)                          | 3.899| 4.278| 5.021| 6.332| 7.895| 10.17| 13.86| 21.43| 42.52| -   |
| axis angle (°)                         | 83.71| 82.12| 83.38| 83.23| 86.07| 88.18| 89.98| 91.23| 92.85| -   |

Table 5 shows the results on the average pitch and diameter as well as the angle of spring axis to the swivel plate normal related to the shift of the feeding mandrel from the swivel plate, c. Because smaller shift might cause numerical instability induced by an initial penetration in contact to the swivel plate, 1.5 mm is taken as the smallest shift for a wire diameter of 1 mm in this study, in which the swivel plate has a normal angle 50° to the Z-direction and a projection angle 45° to the X-direction listed in Table 3 with Euler angles α=32.80° and β=40.12°. It can be found that there is a significant relationship of the diameter to the shift but no significant influence of the shift on the pitch and the spring axis angle. The larger the shift, the larger the spring diameter.
Table 5. Pitch, diameter, and axis angle obtained with different shift of the feeding mandrel to the swivel plate

| shift c (mm) | 1.5  | 2    | 3   | 5  |
|-------------|------|------|-----|----|
| pitch (mm)  | 1.020| 1.018| 1.003|1.039|
| diameter (mm)| 7.407| 10.17| 15.82|27.02|
| axis angle (°) | 84.88| 88.18| 85.07|85.71|

Table 6 shows the results related to the wire diameter. Due to the fact that smaller shift might cause numerical instability induced by an initial penetration in contact to the swivel plate mentioned in section 3.3, 5 mm is taken as the shift for this study. It can be found that there is a significant relationship of the pitch to the wire diameter, while no significant influence of the wire diameter on the spring diameter and the axis angle.

Table 6. Pitch, diameter, and axis angle obtained with different wire diameter

| wire diameter (mm) | 0.5  | 1    | 2   | 5 |
|--------------------|------|------|-----|---|
| pitch (mm)         | 1.021| 1.039| 2.067|5.580|
| diameter (mm)      | 27.93| 27.02| 26.79|27.88|
| axis angle (°)     | 86.15| 85.71| 88.55|76.64|

4. Conclusion

A finite element analysis with a commercial code LS-DYNA on forming cylindrical helical coil springs by a CNC wire bending machine with a swivel plate as the forming die has been conducted in this study. Parameters, such as the angle of the swivel plate, shift distance, and wire diameter, on the formed cylindrical helical coil springs. The results show that the angle of the swivel plate normal to the wire feeding direction and shift distance have a significant effect to the spring diameter, while the wire diameter has a significant effect to the spring pitch. The direction of the swivel plate normal projected on the plane perpendicular to the wire feeding direction shows no significant effect on the spring geometries for a certain angle of the swivel plate normal to the feeding direction. As a result, more curvature can be brought into the sheet metal part by using the sawtooth zigzag path than by using the triangle or rectangle zigzag path. The more impression applied to the metal sheet from the bottom roll, the more curvature can be carried out in the part. The smaller the diameter of the impression roll, the more curvature can be achieved as well. However, the thinner and the stiffer the sheet metal, the more curvature can be realized onto the shaped sheet metal part.

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