Performance Improvement of the Paper-Cup Forming Machine by Barrel Cam Optimization


Abstract—A paper cup forming machine can produce a maximum of about 140 paper cups a minute. If the rate of production is increased to improve productivity, the contact force in the barrel cam increases, and as a result, more vibration is produced. Therefore, a method for reduction of cam vibration is needed. The profile of the barrel cam is optimized by using a multibody dynamics model. The objective of the optimization is to minimize the contact force that occurs between the rollers and the barrel cam. An experiment is carried out using the optimized barrel cam. The reduction of vibration at higher rates of production than the current rates validated the optimization.

Keywords—Barrel cam, Contact force, Multibody dynamics, Optimization, Paper-cup forming machine.

I. INTRODUCTION

The demand for paper cups is increasing rapidly due to their convenience and effectiveness in protecting the environment. To satisfy the demand, current productivity also should be increased. However, simply increasing productivity would result in vibration at the bed on the machine which is a serious problem. When the machine is also affected by the vibration on the bed, defective paper cups are produced. Fig. 1 shows the current paper cup forming machine. The current machine can produce 140 paper cups per minute. If the productivity is increased, the barrel cam will wear out very quickly and the barrel cam will have to be changed. The paper cup is formed on the turret in the paper cup forming machine, and an index with 7 rollers is connected to the turret. The barrel cam makes the rollers move as the cam rotates, so the turret also rotates. Contact force occurs between the barrel cam and the rollers. After the paper cup forming machines operates for a long time, wear occurs on the surfaces of the barrel cam and the roller because of the contact force. Then vibration and noise increase greatly, requiring replacement of the barrel cam and the rollers should be changed.

In this study, the barrel cam profile is optimized to minimize the contact force between the rollers and the barrel cam [1,2]. A multi-body dynamic model is created using ADAMS to calculate the contact force. In order to choose the design parameters, which significantly affect the response variables, sensitivity analysis is performed by using the Plackett-Burman design table. Then, experiments are carried out according to the central composite design table. Next, using response surface analysis, the second order recursive model function, which provides information on the relationship between the design parameters and the response variables, is estimated. The reliability of the estimated model function is verified according to the analysis variance (ANOVA) method. Finally, the sequential quadratic programming (SQP) method is used to find the values of the design variables that minimize the model function and satisfy the linear or nonlinear constraint conditions [3,4]. To verify the reliability of the optimization procedure, a multi-body simulation model of the paper-cup forming machine is created. The contact force between the barrel cam and the rollers of the current and the optimized system is compared. In addition, an experiment using a prototype of the barrel cam is carried out. The vibration on the bed of the paper-cup forming machine between the current and the optimized system is compared.
II. DYNAMIC ANALYSIS

A. Multibody Dynamic Model

The dynamic model of the paper-cup forming machine is created to analyze the contact force between the barrel cam and the rollers by using a multi-body dynamic analysis program ADAMS as shown in Fig. 2. The index drive in a paper cup forming machine is a component that rotates or stops to connect each production process. The index drive is operated by the barrel cam. The dynamic model is composed of 24 parts. Joint, driver spring and contact are defined in the model. The model has a total DOF of 22. The 3D model of the barrel cam is created by using reverse-engineering as shown in Fig. 3. The real product is measured using a laser scanner, which, in this study, is a non-contact measurement laser probe. It measures about 1000 points, and points are connected by a line and converted to a surface to make a 3D solid model in the 3D CAD program.

B. Contact Force Estimation

Fig. 4 shows the analysis result of the contact force between a roller and the barrel cam. In three sections, the contact force increases greatly. Fig. 5 shows the moment when a roller passes by the guide groove of the barrel cam. The first spot indicates the roller entering the guide groove; the second indicates the roller passing through the rotational section; and the last indicates roller escaping the guide groove. The three wear spots coincide with the parts where the contact force increases greatly. The barrel cam is worn out very much in these three parts. The wear often occurs not on the whole surface of the groove but at some points of the groove. Therefore, the contact force can be a very important factor of the barrel cam wear.

III. OPTIMIZATION

A. Design Factors and Level

The contact force is an important factor of the wear, and is closely related to the shape of the barrel cam. The objective function of the optimization is to determine the optimal shape of the barrel cam that minimizes the contact force between the rollers and the barrel cam. The peak value of the contact force is chosen to be minimized. The design factors that can be changed are selected considering the structure of the current system and the interference of other parts. And the modified sine curve giving the best performance considering the force transfer efficiency is still used. Among the many design variables, the radius and height of the roller and the radius of the index are selected. These three parameters are determined as design factors through engineering discussion. Table 1 presents the height and radius of the roller and the radius of the index which are set as design factor.

<table>
<thead>
<tr>
<th>Variables</th>
<th>Min (-1)</th>
<th>Current (0)</th>
<th>Max (+1)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Radius of Roller (mm)</td>
<td>12.7</td>
<td>31.75</td>
<td>38.1</td>
</tr>
<tr>
<td>Height of roller (mm)</td>
<td>15.875</td>
<td>38.1</td>
<td>44.45</td>
</tr>
<tr>
<td>Radius of index (mm)</td>
<td>180.0</td>
<td>203.0</td>
<td>206.5</td>
</tr>
</tbody>
</table>

B. Response Surface Analysis

An orthogonal array of the design factors is created. Fifteen experiments are carried out based on the orthogonal array of three design factors. Based on the experimental results, the response surface analysis method deduces the response function, a mathematical correlation between the design factors and system performances by using a statistical method. When
there are many design factors, a quadratic regression model is generally used as the response function because of the nonlinearity of the relation between the design factors and system performances. In this study, the central composite design table including the central point and the axial point is used in 2-level factor experiments to estimate the model function. Based on the result, a quadratic regressive model function is derived using the method of least squares. The regressive model function obtained in the study is expressed as

\[ Y = -790 + 30800R_r + 63520R_h - 148580I_r \\
- 215600R_r^2 + 61450R_h^2 + 73920I_r^2 \\
+ 74670R_rR_h + 23140R_hI_r - 193190R_hI_r, \]

where \( Y \) is the contact force between the barrel cam and roller, \( R_r, R_h \) and \( I_r \) is the radius of roller and height and radius of index, respectively. To obtain the values of the design factors that minimize the objective function, the SQP method is used. The SQP is an efficient optimal algorithm that obtains the lowest values of a function given more than two design factors and nonlinear constraint conditions. Table 2 shows the values of the design factors that minimize the objective function.

<table>
<thead>
<tr>
<th>TABLE II</th>
<th>OPTIMIZED DESIGN VARIABLES</th>
</tr>
</thead>
<tbody>
<tr>
<td>Design Parameter</td>
<td>Value (mm)</td>
</tr>
<tr>
<td>Radius of Roller</td>
<td>23.8125</td>
</tr>
<tr>
<td>Height of roller</td>
<td>25.4</td>
</tr>
<tr>
<td>Radius of index</td>
<td>204.7225</td>
</tr>
</tbody>
</table>

C. Verification

To verify whether the optimization has been carried out well, a dynamic model is created using the optimized barrel cam model. And the contact force of the current and the optimized model is compared. The contact forces of 2 rollers are compared in fig. 6. The peak value of the contact force remarkably decreases between the barrel cam and the rollers after optimization. The change of the contact force is shown in Table 3. The peak value of the contact force between the barrel cam and the roller decreases about 82.24%. Also the RMS value of the contact force decreases about 76.37%. Therefore the optimization using the dynamic model is verified.

![Fig. 6 Contact force between roller and barrel cam](image)

![Table III](image)

<table>
<thead>
<tr>
<th>TABLE III</th>
<th>ESTIMATED RESULT OF THE OPTIMIZED SYSTEM</th>
</tr>
</thead>
<tbody>
<tr>
<td>Variables</td>
<td>Current</td>
</tr>
<tr>
<td>Average of peak value of contact force (N)</td>
<td>29,186</td>
</tr>
<tr>
<td>RMS value of contact force (N)</td>
<td>5,541</td>
</tr>
</tbody>
</table>

IV. CONCLUSION

In this study, the design of the paper-cup forming machine was optimized to decrease the contact force between the barrel cam and the rollers. The contact force was analyzed using a dynamic model of the barrel cam and the index unit, which is an operating part of the paper cup forming machine. Through engineering discussion, the design factors and their values were determined for the optimization.

The radius and height of the roller and the radius of the index were optimized. And the shape of the barrel cam was also optimized according to the radius and height of the roller and the radius of the index. To verify the reduction of vibration using the optimized components in this study, the contact force was analyzed. The contact force significantly decreased in the dynamic model with the optimized components. In addition, the acceleration of the bed of the paper-cup forming machine was measured by experiments. The acceleration decreased in the optimized system. In conclusion, with the optimized roller, index and barrel cam, the paper-cup forming machine can operate at a high speeds with low wear.

REFERENCES

Development of flexible multi-body dynamics analysis program of solar cell manipulator with position control

Wook Hyeon Kim, Tae Won Park and Dong Il Park

Abstract—The solar energy is converted to electric energy on solar cell. While the solar cell is manufactured, the solar cell manipulator transports the solar cell in each process. The manipulator picks and places the solar cell on its forks. The size of solar cell is growing larger to convert more solar energy to electric energy. Manipulator forks need to get larger corresponding to the size and operate stably for accurate positioning. In this study, a program is developed to create and control a multi-body dynamics model of solar cell manipulator. The flexible multi-body dynamics model is created using the developed program. The model contains multi-body dynamics model and control model. Though two models are analyzed separately, some parameters are shared by each model to integrate the models.

Keywords—Solar cell manipulator, Multi-body dynamics, Flexible link, Control model

I. INTRODUCTION

The solar energy which is one of alternative energy converted to electric energy on a solar cell. The solar energy makes electron on solar cell move to electrode and the movement of electron is converted to electric energy. The solar cell is produced on a glass substrate using silicon crystal. The size of solar cell is growing larger by generation to produce more electric energy. In manufacturing process, the solar cell is transferred by manipulator on its fork. When the solar cell glass was small, the characteristic of forks was not so important. However, as the generation of solar cell is progressed, the length of fork gets longer to cover the size of solar cell glass. So deflection, vibration, weight and other characteristic of fork is gradually taken into consideration because these problems may cause error of positioning of manipulator. In this study, a program to investigate the characteristic of solar cell manipulator is developed. A flexible multi-body dynamics model with position control is created using the developed program. The manipulator has large rotational or translational operation. Relatively the fork has small deformation on its tip. So floating frame of reference frame method (FFRF) is used to present the flexible body.[1-5] The displacement of the solar cell manipulator and deflection of manipulator fork is analyzed while the manipulation is operation in normal condition. The result is compared to the commercial flexible multi-body dynamics analysis program to verify the developed program. The tip of manipulator fork should converge to stable state quickly. If not, the time for one cycle in normal operating condition would increase and it may result in poor productivity. State-space equation of fork is derived and control force equation is defined using gains. The force equation is applied to the developed program for accurate positioning of manipulator fork.[6-8]

II. FLEXIBLE MULTI-BODY DYNAMICS MODEL OF SOLAR CELL MANIPULATOR

Fig. 1 shows the solar cell manipulator. The multi-body dynamics model of solar cell manipulator is composed of rigid bodies and flexible bodies. Most of the bodies are assumed to be rigid bodies as they have small deformation that can be neglected. However, the fork of the solar cell manipulator is...