Quasi Static Analysis of Heald Frame Driven by Rotary Dobby with Cam-linkage Modulator

YU Hongbin a, *, YIN Honghuan a, PENG Junqiang a, WANG Lei b

a School of Mechanical Engineering, Tiangong University, Tianjin 300387, China
b School of Mechanical Engineering, Tianjin University, Tianjin 300072, China

Received 10 December 2019; accepted for publication 30 March 2020

Abstract

In this paper, the motion characteristics of a cam-linkage modulator, a cam unit and a motion transmission unit were analyzed in order to establish a quasi static model, explored their motion characteristics, and identified the factors affecting the stability and reliability of the heald frame motion. Based on the mapping points, the conjugate cam profile was established using non-uniform rational B-splines and a mathematical model of the motion process from the uniform rotation motion input of the dobby to the vertical variable output of the heald frame was constructed. Additionally, an analytical method for each motion transmission process was established and a numerical programming method was developed. The displacement, velocity and acceleration of the modulator, cam unit and heald frame were simulated and measured using a motions simulation and test bench, and the analysis, simulation and verification results were compared. The results show that the motion characteristics of the heald frame can be obtained through the cam-linkage modulator, cam unit and the motion transmission unit. The accuracy of the constructed model was verified which lays the foundation for further exploration of more stable, reliable and high-speed dobby mechanisms that will meet the requirements of a new generation of looms.

Key Words: Rotary dobby, Quasi static model, Motion characteristics, Cam-linkage modulator, Heald frame

1. Introduction

In textile machinery, a dobby, which is also known as a ‘dobby lifting device’, is a type of commonly used shedding device applied to shuttle less looms. A rotary dobby is a type of positive dobby that operates on a rotary principle with digital control. As looms are shedding at ever faster speeds, a new generation rotary dobby offering speeds of up to 1000 ~ 1500 rpm has been developed, which makes it possible to use rotary dobby on high-speed air jets or water jet looms.

Dobby construction can be classified according to their shedding principles, program controlling principles, construction, and the motion transmission mechanism to the heald frames [1]. Abdulla et al. [2] introduced an electronically controlled positive driven dobby construction method for dobbies with sixteen lifting arms and middle closing that can offer speeds of up to 604 rpm, with an accessible manufacturing cost and acceptable level of working noise. The referenced [3, 4] universal mathematical model for the shedding motion can be simplified by entering a time dependent lift dependence on the driving element to define the course of its angular displacement. Analysis of the driving section generated by rotary dobby or cam shedding motion has been presented in several previous studies [5-7]. Guo [8] introduced a new type of microprocessor-controlled dobby which is a conversion of the dobby of the Staubli2521 model. The new model has been proven to be practical, simple and easier to manufacture than present positive dobbies. Shen [9, 10] analyzed the motion mechanism of the rotary dobby GT241, established a quasi static model for the main transmission component of the rotary dobby, and performed related motions simulation research. Since the transforming section of the shedding motion is a joint mechanism, a number of procedures and methods can be employed to model this structure [11, 12]. The mechanism can be successfully described by devising motion equations using the Lagrangian equations [11]. This mathematical model has been described in detail elsewhere [12, 13]. A simple heald model to obtain its motion during the weaving process has been previously described [12]. However, this model can only realize basic analysis of the system motion due to its simplicity. To directly analyze the motion of the heald frame during the weaving cycle, the mathematical model needs extension and

* Corresponding author: E-mail: yuhongbin@tiangong.edu.cn, Tel: 0086-13323321892
elaboration. A model that substitutes the rigidity of the heald frame using the Kelvin-Voigt viscoelastic model has been proven suitable to generate an improved mathematical model [13]. Zhang [14] established a rotation variable speed mechanism of a dobby based on Creo software and motion simulation analysis was performed. Jin [15] established a dynamic model of the mechanism using the Lagrange equation and analyzed the accuracy and validity of the proposed dynamic model. Another study considered the reduction in the heald frame velocity before its drop onto the supporting wire due to the opposite section of the heald frame pressing into the rubber element. The results that were calculated using the new concept with the heald frame attached to the dobby were compared to the existing solution without application of the damping element [16].

Previous research was mainly based on the cam motion transmission mode of the crank slider and focused mainly on simulation without corresponding experimental research and verification. This paper introduces a quasi static model of the heald frame driven by a rotary dobby with cam-linkage modulator. The cam modulated linkage, also known as the cam-integrated linkage or the combined cam-linkage mechanism, is a composite mechanism consisting of at least one cam-follower pair in combination with a linkage [17-22]. In this quasi static model, it is possible to ascertain the characteristics of the modulator, the cam unit and the motion transmission unit (MTU) as well as the characteristics of the transfer between the rotary dobby and the heald frame. Using this mathematical model, the displacement curves, velocity and acceleration of the modulator, cam unit and heald frame can be determined. The analysis, simulation and verification all show that motion curves with continuous acceleration should be chosen to prevent impact speed, stress and noise in mechanism.

Fig. 1 shows the research workflow. Firstly, using 200 mapping points measured by a three-coordinate measuring machine, a non-uniform rational B-splines (NURBS) [23, 24] was used to fit the cam profile. Based on this profile and the analysis of the working principle of the motion mechanism, a quasi static model of the heald frame driven by a rotary dobby with a cam-linkage modulator was established. The theoretical numerical analysis was then undertaken using programming methods. A virtual prototype was also established and a motion simulation of the prototype was completed using Solidworks Motion software. Finally, a dobby motion performance testing bench [25] was built to measure movements of the modulator, cam unit and heald frame. The simulation and experimental results verify the accuracy of the quasi static model of the heald frame driven by a rotary dobby with a cam-linkage modulator. The research in this paper provides the necessary theoretical basis and guidance to improve the motion performance and reliability of a rotary dobby.

2. Principle of movement of a heald frame

Rotary dobby mechanisms are normally built to control either 12, 16, 20, 24, 28 or up to 32 heald frames. Based on different control signals, the cam unit drives the heald frame movement to meet the loom as required by the weave. Each lifting arm of the rotary dobby has the same motion characteristics and each arm is used to drive one corresponding frame. The principle of movement of the heald frame is shown in Fig. 2.

The parts that constitute the cam-linkage modulator are labelled in Fig. 2 as follows: large gear (1), conjugate cams (5 and 11), cam rollers (3, 6, 10 and 14), cam swing arms (2, 8, 9 and 15), modulator links (4 and 7) and main shaft (13). The conjugate cams are fixed to the rotary dobby housing body and the uniform circular motion of the loom shaft is transmitted to the large gear. The four cam...
swing arms are hinged to the large gear and motion is transmitted to the four identical cam rollers to move them along the main cam and the auxiliary cam profile of the conjugate cam, tangentially to the conjugate cam profile. Two of the cam rollers (3 and 10 in Fig. 2) and the modulator links are hinged by the cam swing arms and motion is transmitted to the main shaft. Therefore, the modulator transforms the uniform rotary motion from the weaving machine into non-uniform rotary motion of the dobby main shaft. A conjugate cam and linkage with precise characteristics can be used to meet the requirements of any type of weaving machine.

In Fig. 2, the eccentric disc cam (12), the ring link (16) and the lifting arm (17) constitute the cam unit of the rotary dobby and realize the reciprocating swing of the lifting arm (17). Each heald frame is controlled by a cam unit that is only 12 mm wide and converts the non-uniform rotary motion of the main shaft (13) directly into the linear motion required for the heald frame drive. The cam unit is a crank mechanism that encloses a cam with ball bearings (which is not shown in Fig. 2). A ratchet placed on the outside of the cam connects it with the driver and a 180° rotation of the cam causes a lifting motion. The ratchet is controlled based on the pattern used by the control unit.

The MTU consists of a four-bar linkage mechanism and a crank slider mechanism. The four-bar linkage mechanism consists of a lifting arm (17), a lifting arm link (18) and a swivel arm (19). The crank slider mechanism consists of a heald frame link (21), a support link (22) and a heald frame (23), which transforms the straight-line motion of the heald frame.

### 3. Quasi static model

There are three main elements of a heald frame driven by a rotary dobby with electronic control based on loom order: a modulator, a cam unit and a MTU.

#### 3.1 Cam-linkage modulator

The cam-linkage modulator is composed of a cam-roller mechanism and a roller-linkage mechanism. A schematic diagram is shown in Fig. 3.

The large gear rotates clockwise at an angular velocity ω and the conjugate cam is fixed to the dobby housing body. For example, in Fig. 3, when the cam roller and the cam are tangential to point B, the cam swing arm is hinged at point O2 and can rotate around this point via the large gear. When engagement happens, the uniform motion of the large gear is transmitted to the cam roller through the cam swing arm. The modulator links hinged at point C can rotate around point O1 via the cam roller leading to rotary motion of the dobby main shaft fixed at point O1.

### 3.1.1 Cam profile by NURBS curve fitting

For the numerical analysis and simulation, 200 points of the cam profile were measured by a coordinate measuring machine (CMM). Fig. 4 provides the coordinates of the cam profile mapping points. Using cubic NURBS curve interpolation to construct the conjugate cam profile of the rotary dobby, a mathematical model of NURBS can be obtained as per the following equation:

\[
P(u) = \sum_{i=0}^{n} N_{i,k}(u) W_i V_i \quad \text{where } V_i \text{ is the control point coordinate, } W_i \text{ is the weight parameter, } n \text{ is the superscript of the additive combination from 0 to } n \text{, the total of } n+1 \text{ control points, } i = 0, 1, \ldots, n, k \text{ is the degree of the NURBS curve with order } k-1, N_{i,k}(u) \text{ is the basis function and } R_{i,k}(u) \text{ is the rational basis function needed to satisfy the following formulas:}
\]

\[
R_{i,k}(u) = \frac{N_{i,k}(u) W_i}{\sum_{j=0}^{n} N_{j,k}(u) W_j}
\]

and if \( k > 1 \),

\[
N_{i,k}(u) = \begin{cases} 1 & \text{if } u \in [u_i, u_{i+1}) \\ 0 & \text{otherwise.} \end{cases}
\]

where \( u_i \) is a node and the vector formed by each node is called the node vector: \( U = [u_0, \ldots, u_n] \).
In order to improve the smoothness of the interpolation curve and ensure that the curve has first-order and second-order continuous derivatives, a fourth-order dobby cam profile is obtained using equations (1) to (4).

### 3.1.2 Cam-linkage modulator

Fig. 5 shows the schematic diagram of the cam-linkage modulator. Point $O_2$ on the large gear is centered on point $O_1$ and the uniform angular velocity $\omega$ and rotation angle $\theta$ are halfway along the loom output (dobby input) shaft, as the rotary dobby has a double lift principle. The mechanism converts changes in the positive angle $\Phi$ between $O_1 A$ and $O_2 C$ to changes in the positive angle $\Phi$ between $O_1 A$ and the $x$ axis, $\theta = \omega t$. The trajectory formed by point $A$ of the cam roller’s center is the theoretical cam profile.

From equations (5) to (10), we can obtain $A(x_A, y_A)$, $\Phi = \arctan \left( \frac{y_A}{x_A} \right)$, where $r$ is the cam roller radius, $A(x_A, y_A)$ is the center point of the cam roller and $T = |O_2 A|$ is the distance from the cam roller center $A$ to the hinge point $O_2$ of the cam swing arm. $R = |O_1 O_2|$ is the distance from the cam center $O_1$ to the hinge point $O_2$.

Based on the change in positive angle $\Phi \in \left[0^\circ, 360^\circ\right)$ between $O_1 A$ and the $x$ axis, the characteristics of the change in positive angle $\alpha$ between $O_1 A$ and $C$ and the $x$ axis can be established in order to obtain the coordinates of point $C$. The motion characteristics of the modulator at point $O_2$ can be obtained based on the changes of point $C$ coordinates.

Using the geometric relationship:

$$ (x_A - x_C)^2 + (y_A - y_C)^2 = R^2 $$

E can be solved according to Equation (11), where $x_C = r_1 \cos a$, $y_C = r_1 \sin a$, $r_1 = |O_1 C|$ is the distance from the main shaft $O_1$ to the hinge point $C$ of the modulator link. $R_1$ is the length of $AC$, and $C(x_C, y_C)$ are the coordinates of point $C$.

Equations (5) to (11) in the mathematical models can be used for quasi-static analysis of the cam-linkage modulator mechanism, which converts continuous rotation of the loom shaft to an intermittent movement of the modulator shaft.

### 3.2 Cam unit

Fig. 6 shows a crank rocker mechanism without snapback characteristics that can move between two extreme positions. Link $E_1 E$ swings between both extreme positions during each revolution of link $D_1 D$. When the crank $D_1 D$ moves to the $D_0 D_1$ position, the swing arm of the rotary dobby is at its lower position and the heald frame reaches the upper shed. When the crank $D_1 D$ moves to the $D_0 D_2$ position, the swinging arm of the rotary dobby is at its upper position and the heald frame reaches the lower shed. Therefore, quasi-static design and analysis of the cam unit of a rotary dobby can be performed using this crank rocker mechanism.
the transmission angle which can be defined as the angle between link DE and link $E_0E$ that satisfies the following equations:

$$l_{DE}/l_{E_0E} = \sqrt{(1 - \cos \phi_6)/2 \cos^2 \mu_{\text{max}}}$$

$$l_{DE}/l_{E_0E} = \sqrt{1 - (l_{DE}/l_{E_0E})^2} \cos \mu_{\text{max}}$$

$$l_{DE}/l_{E_0E} = \sqrt{(l_{DE}/l_{E_0E})^2 + (l_{E_0E}/l_{E_0D})^2 - 1}$$

Fig. 6 presents a schematic diagram of the cam unit of the rotary dobby. The angular displacement of link $E_0E$ relative to link $D_0D$ is obtained by the cam unit rotation. The center of rotation $D_0$ of link $D_0D$ is the modulator axis $O$, and the angle between link $D_0D$ and the x axis is the positive angle $\phi_1 = \alpha$.

Using the geometric relationship, $\phi_1$ can be found from Equation (12):

$$\begin{align*}
\{ l_{DE} \cos \phi_1 + l_{E_0E} \cos \phi_2 - l_{E_0D} \cos \phi = l_{DE}, \\
l_{DE} \sin \phi_1 + l_{E_0E} \sin \phi_2 = l_{E_0D} \sin \phi
\end{align*}$$

(12)

3.3 MTU

The motion transmission unit (MTU) for the heald frame is composed of a four-bar linkage mechanism and a slider crank mechanism.

3.3.1 Four-bar linkage mechanism

Fig. 7 shows the schematic diagram of the four-bar linkage of the MTU. Link $E_0F$ is the lifting arm of the dobby, link $E_0E$ is rigidly coupled to link $E_0F$ at an angle $\beta_1$ around point $E_0$ and the positive angle between link $E_0F$ and the x axis is $\phi_4$.

The four-bar linkage mechanism of the motion transmission unit is similar to the motion analysis equations of the cam unit mechanism. The angular displacement $\phi_1$ of link $G_0G$ relative to link $E_0F$ can be calculated as follows:

$$\begin{align*}
\{ l_{DE} \cos \phi_1 + l_{E_0E} \cos \phi_2 - l_{E_0D} \cos \phi = l_{DE}, \\
l_{DE} \sin \phi_1 + l_{E_0E} \sin \phi_2 = l_{E_0D} \sin \phi
\end{align*}$$

(13)

$\phi_1$ can be obtained from Equation (13), where $\phi_1 = 180^\circ - \beta_1$ - $\phi_2$.

$\beta_1$ is known, $\phi_2$ is obtained during the analysis of the cam unit described above.

3.3.2 Slider crank mechanism

The angular displacement $\phi_6$ of link $G_0G$ is obtained using the four-bar linkage mechanism analyzed above. Fig. 8 shows the schematic diagram of the slider crank mechanism of the MTU. Link $G_0G$ is rigidly connected to link $G_0H$ and equation (14) is the quasi static analysis equation which relates the heald frame displacement to the angular position of link $G_0H$.

The rotational motion of link $G_0H$ is transformed into the straight-line motion of slider ‘I’ through the following geometric relationships:

$$\begin{align*}
\sin \phi_1 = (l_{DE} \cos \phi_1 - e)/l_{DE}, \\
S = l_{DE} \cos \phi_1 - l_{DE} \cos \phi_6
\end{align*}$$

(14)

where the angle between link $G_0H$ and the y axis is $\phi_1 = \phi_6 + \beta_2$.

$\beta_2$ and $e$ are the known parameters in the slider crank mechanism structure. $\phi_6$ is obtained using the four-bar linkage mechanism described previously and $S$ is the displacement of the heald frame. The MTU also includes connecting links $GJ$, $J_0J$, $J_0K$ and KL with links $J_0J$ and $J_0K$ rigidly connected and a joint point $J_0$, resulting in linear motion of slider ‘L’ along the y axis. The same components are used for slider ‘L’ and ‘I’.

4. Analysis, Simulation and Verification

In this section, the motion characteristics of the modulator, cam unit and heald frame will be obtained. The numerical analysis is completed based on the cam profile fitted by the NURBS curve and the quasi static model of the heald frame driven by the rotary
dobby with the cam-linkage modulator. The motion simulation is performed using the established virtual prototype of the modulator, cam unit and heald frame. Finally, experimental verification is undertaken by obtaining actual motion data based on the heald frame motion performance of the test bench.

4.1 Analysis

The parameters of the modulator and the heald frame are shown in Table 1. The corresponding components of the modulator are the same size as the Staubli2871 rotary dobbi [17], and the parameters of the heald frame are the same as the dobbi test bench. The test bench is depicted in Fig. 9, where the mechanical device is shown to be appropriately coupled to electronic systems for the acquisition, storage and processing of experimental data. It mainly consists of rotary dobbi, drive motor, modulator, cam unit, MTU, heald frame and control system. It simulates the whole process of dobbi driving heald frame movement in the weaving process.

Visual Studio 2012 was used to develop a program using the data in Table 1 and equations (5) to (14). The rotational speed of the rotary dobbi input motor was set to 10 rpm. Two work cycles were calculated and the displacement, velocity and acceleration curves of the modulator, cam unit and heald frame were obtained.

4.2 Simulation and Verification

In order to verify the correctness of the numerical analysis, a virtual prototype of the rotary dobbi and the heald frame shedding control mechanism is developed using SolidWorks 2016 software. The virtual prototype in Solidworks using the same simulation conditions as the theoretical analysis. The motion simulation was performed on the heald frame driven by the rotary dobbi with the cam-linkage modulator. Finally, the simulation motion characteristics of the heald frame are given.

The verification motion characteristics of the modulator and the heald frame were obtained using the dobbi test bench (as shown in Fig. 9). However, the motion characteristics of the cam unit cannot be obtained using this method.

The same test conditions were used as for the numerical analysis and motion simulation. In order to measure the speed of different positions, three 2000 ppr encoders were selected, which were connected to the motor shaft, the modulator output shaft and the heald frame respectively. The encoder pulse time data was acquired by the logic analyzer. The verification motion characteristics are obtained.

5. Results and discussion

The motion characteristics of the modulator, cam unit and heald frame were analyzed through numerical analysis, motion simulation and experimental verification. The deviations between the three methods were also obtained, as shown in Figs. 10 to 12 and Table 2.

| Table 1 | Parameters of modulator, cam unit and MTU. |
|---------|-------------------------------------------|
| Modulator | Value | Cam unit | Value | MTU | Value |
| \( r \)(/mm) | 31 | \( l_{D_1G} \)(/mm) | 30 | \( l_{HG} \)(/mm) | 550 |
| \( r_1 \)(/mm) | 47 | \( l_{HE} \)(/mm) | 170 | \( l_{O_1G} \)(/mm) | 150 |
| \( R_1 \)(/mm) | 81 | \( l_{E_1G} \)(/mm) | 96 | \( l_{O_1H} \)(/mm) | 200 |
| \( T \)(/mm) | 56 | \( l_{E_2G} \)(/mm) | 185 | \( l_{E_2J} \)(/mm) | 695 |
| - | - | \( l_{D_2E_1} \)(/mm) | 207 | \( l_{H_1} \)(/mm) | 375 |
| - | - | - | - | \( \beta_1 \)(/°) | 90 |
| - | - | - | - | \( \beta_2 \)(/°) | 90 |
| - | - | - | - | \( \psi \)(/mm) | 198 |
(a) Motion characteristics of the modulator
(b) Deviations of the modulator

Fig. 10  Modulator motion characteristics and deviations.

(a) Motion characteristics of the cam unit
(b) Deviations of the cam unit

Fig. 11  Cam unit motion characteristics and deviations.

(a) Motion characteristics of the heald frame
(b) Deviations of the heald frame

Fig. 12  Heald frame motion characteristics and deviations.
Table 2  Range of deviations for 'Analysis vs Simulation' and 'Analysis vs Verification'.

| Modulator | Analysis vs Simulation | Analysis vs Verification |
|-----------|------------------------|--------------------------|
| V (deg/s) | -1.70 – 2.04           | -3.08 – 2.66             |
| A (deg/s²) | -22.27 – 9.94         | -33.00 – 15.44           |
| D (deg)  | -0.32 – 0.28          | -                       |

| Cam unit | Analysis vs Simulation | Analysis vs Verification |
|----------|------------------------|--------------------------|
| V (deg/s) | -0.30 – 0.40          | -                        |
| A (deg/s²) | -3.95 – 3.09        | -                        |
| D (mm)  | -1.31 – 0.68          | -5.09 – 0.61             |

| Heald frame | Analysis vs Simulation | Analysis vs Verification |
|------------|------------------------|--------------------------|
| V (mm/s)  | -1.74 – 1.85          | -3.00 – 6.63             |
| A (mm/s²) | -14.77 – 15.47        | -10.02 – 26.25           |

The letters 'D', 'V', and 'A' following the '-' symbol in Fig. 10 to Fig. 12 represent displacement, velocity, and acceleration, respectively. Table 2 is obtained using the data in Fig. 10 (b), Fig. 11 (b) and Fig. 12 (b) and shows the deviations range for 'Analysis vs Simulation' and 'Analysis vs Verification'. The modulator, cam unit and heald frame analysis motion curves are very similar to the simulation curves. Some deviations between the verification motion curves and the analysis motion curves can be observed, due to interference by vibration, noise and the experimental measurement method but it is within a controllable range. It can be concluded that the established quasi static model and motion analysis of the heald frame driven by a rotary dobby with a cam-linkage modulator is reliable. The following analysis is based on these calculations.

Fig. 10 shows the angular displacement, angular velocity and angular acceleration of the modulator output shaft with respect to a large gear angle. When a cam-linkage mechanism is employed in the modulator, uniform dobby input motion can be used to obtain precise non-uniform motion and dwell periods with the desired motion characteristics at the modulator output shaft. As seen in Fig. 10, over a 720° motion period of the large gear, the modulator shedding motions generate maximum velocities and accelerations which are very close to each other without any dwell in the modulator output shaft movement. The modulator output shaft has four acceleration phases and four deceleration phases in two motion cycles. Its angle is half of the movement period of the modulator output shaft given by the main shaft angle of the loom. Non-uniform rotary motion ensures that the modulator turns through 180° and then pauses momentarily for a new selection.

Fig. 11 shows the angular displacement, angular velocity and angular acceleration of the cam unit. It can be seen clearly when comparing Fig. 10 with Fig. 11 that there is some dwell occurring in the cam unit movement even without a dwell in the modulator output shaft movement. Over the interval $\alpha \in (0°, 180°] \cup (360°, 540°)$, link $E_o F$ of the cam unit accelerates from its rearmost position and becomes uniform before descending to its most forward position. Over the interval $\alpha \in (180°, 360°] \cup (540°, 720°)$, link $E_o F$ of the cam unit accelerates from its most forward position and becomes uniform before finally decelerating to its rearmost position again.

Fig. 12 shows the displacement, velocity and acceleration curves of the heald frame over two cycles of the large gear. It can be clearly seen from the curves that the motion characteristics of the heald frame have the same form as the motion characteristics of the cam unit. The heald frame motion has a longer dwell at the lower and upper positions, which can be seen more clearly in the heald frame speed and acceleration curves in Fig. 12 (a). Over the interval $\alpha \in (180°, 360°] \cup (540°, 720°)$, the heald frame accelerates from its upper position and then becomes uniform before descending to the lower position. Over the interval $\alpha \in (0°, 180°] \cup (360°, 540°)$, the heald frame accelerates from its lower position and then becomes uniform before finally decelerating to its upper position again. This result shows that the motion transmission mechanism does not have a significant impact on the motion characteristics of the heald frame. The effect of the cam unit on the heald frame motion can be seen more clearly by comparing Fig. 11 (a) with Fig. 12 (a). The maximum displacement, the maximum velocity and the maximum acceleration of the heald frame are much higher with the rotary dobby than with the cam unit shedding motions.

The modulator output shaft and the corresponding heald frame both pause four times during two motion cycles. When the heald frame reaches the lower or upper position, the shed opens, as required by the actual working conditions of the loom. A significant period of the heald frame dwell is obtained without any dwell in the modulator output shaft motion. A 180° rotation of the modulator leads to approximately a 50° upper dwell period and a 60° lower dwell period for the motion of the heald frame due to the cam unit. These values can deviate depending on the design of the cam-linkages in the modulator mechanisms and the motion curves chosen for the follower motion in the cam unit mechanism and the MTU. The maximum motion characteristics of the heald frame are dependent on the general maximum heald frame displacement level, the maximum heald frame velocity and the maximum heald frame acceleration. This is especially important for high speed air jets and water jet looms where the heald frame acceleration should be reduced in order to minimize the inertial forces while leaving a sufficient level of shed openness for weft insertion.

6. Concluding remarks

A quasi static model and analytical method of the cam-linkage modulator, the cam unit and the heald frame have been established and a virtual prototype simulation analysis has been completed. Experimental verification was also performed using a performance test platform of a heald frame. The analysis, simulation and verification results were compared and the results were basically unanimous and showed the motion characteristics of the heald frame.
Heald frame motion is mainly determined based on the design of the modulator. The cam profile plays an important role in the cam-linkage modulator. The cam unit has a significant influence on the motion characteristics of the heald frame, as it has the same form as the motion characteristics of the cam unit. The motion transmission mechanism does not effectively change the motion characteristics of the heald frame, but only magnifies the motion characteristics of the cam unit.

More research should be completed to ensure that the modulator, cam unit and heald frame have continuous speed, acceleration and an even jerk curve to prevent impact stress and noise in the mechanism.

References
[1] Adanur S (2000) Handbook of Weaving, CRC Press, 110-116
[2] Abdullayev G, Palamutcu S, Soydan AS, Hascelik B (2006) Tekstil, 55, 184-188
[3] Eren R, Özkan G, Turhan Y (2005) Fibres & Textiles in Eastern Europe, 13, 78-83
[4] Eren R, Özkan G, Karahan M (2008) Textile Research Journal, 78, 1070-1079. https://doi.org/10.1177/0040517507083549
[5] Korolev PA, Lohmanov VN (2011) Lzvestiya Vysshikh Uchebnykh Zavedenii, Seriya Teknologiya, 4, 116-119
[6] Sadettin K, Taylan DM, Ali K (2010) Gazi University Journal of Science, 23, 227-232
[7] Abdulla G, Hasçelik B, Palamutcu S, Soydan AS (2010) Tekstil ve Konfeksiyon, 20, 218-224
[8] Guo YY, Chen RQ (2003) Indian Journal of Fibre & Textile Research, 28, 275-280
[9] Gao DN, Shen Y, Liu CL (2012) Advanced Textile Technology, 20, 27-31. https://doi.org/10.19398/j.att.2012.01.008
[10] Shen Y, Gao DN, Liu CL (2012) Journal of Textile Research, 33, 119-123. https://doi.org/10.13475/j.jtxr.2012.08.027
[11] Mrazek J (1992) Mechanism and Machine Theory, 27, 331-341. https://doi.org/10.1016/0094-114X(92)90023-B
[12] Bílek M, Mrazek J (1998) Fibres and Textiles, 3, 131-134
[13] Bílek M, Skřivánek J (2013) Autex Research Journal, 13, 44-50. https://doi.org/10.2478/v10304-012-0022-8
[14] Zhang YH, Gou XF, Chen XF, Wang ZL (2018) Journal of Mechanical Transmission, 42, 57-61. https://doi.org/10.16578/j.issn.1004.2539.2018.04.012
[15] Jin GG, Wei XY, Wei Z, Chang BY, Zhang XY (2018) Journal of Textile Research, 39, 160-168. https://doi.org/10.13475/j.fzxb.20171104709
[16] Bílek M, Skrivánek J (2015) Autex Research Journal, 15, 1-7. https://doi.org/10.2478/aut-2014-0038
[17] Documents of 2670 Staubli rotational dobby. http://www.doc88.com/p-703223254379.html
[18] Singh YP, Kohli D (1981) Mechanism and Machine Theory, 16, 447-457. https://doi.org/10.1016/0094-114X(81)90017-3
[19] Erdman AG, Sandor GN, Kota S (2001) Prentice-Hall, Englewood Cliffs, 1, 426-435
[20] Ye Z, Smith MR (2005) Proceedings of the Institution of Mechanical Engineers, Part C: Journal of Mechanical Engineering Science, 219, 419-427. https://doi.org/10.1243/095440605X16884
[21] Mundo D, Danieli GA, Yan HS (2006) Transactions of the Canadian Society for Mechanical Engineering, 30, 519-532. https://doi.org/10.1139/tcsme-2006-0033
[22] Mundo D, Liu JY, Yan HS (2006) Journal of Mechanical Design, 128, 1253-1260. https://doi.org/10.1115/1.2337317
[23] Wang Y, Chen JN, Zhao X, Zhang GF, Yu BB (2013) China Mechanical Engineering, 24, 1375-1380. http://www.cmemo.org.cn/EN/Y2013/V24/I10/1375
[24] Sun H, Chen ZM, Ge WJ (2006) Higher Education Press, 117-120
[25] Yin HH, Yu HB, Jin YL, Li XK (2016) ICMEIT, Xi an, China, 27 August - 01 September, 57, 343-348