Computer Simulation of Warp Tension on a Weaving Machine

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Abstract

This paper investigates about the simulation of warp tension variation in a weaving machine, based on mathematical and mechanical equations. To perform simulation, a differential equation system was formed and solved by numerical method. The results shown as the curves of warp tension variations and back rail oscillation of the loom were compared with the experimental results obtained from warp tension measurement. The result of comparison showed a good agreement between the theoretical and experimental results.

Keywords: Warp tension, Computer simulation, Numerical method, Differential equation system

1. Introduction

The increase in the operating speed of modern weaving machines has made the weaving process more difficult, as even small errors in machine settings can lead to repeated stoppages and cause cloth faults. To avoid these faults the weaving machines provide numerous setting possibilities so that to achieve optimum operation at the higher weaving speeds.

Warp tension is one of the parameters to be carefully controlled on a loom, so as to avoid excessive peak tension values, as well as too low values of it, which would lead to unsatisfactory shedding. A computer simulation of warp yarn tension during weaving is aimed to therefore help in creating objective setting recommendations for weaving machines.

To determine the combined effect of a given combination of the factors such as loom, weave and warp ends material on a loom on a routine basis will be time consuming, uneconomic and sometimes impracticable. To avoid these, the loom and forces involved in determining warp tension can be mathematically modelled and the effects of different factors on warp tension may be examined.

2. Specifications of Loom, Weave and Warp, Used in Present Work

For the work reported in this paper, a weaving loom of Sulzer-Ruti company, with 240R.P.M speed (4 picks/sec.), 6 heald shafts, balanced shed geometry, late shed timing, shed closing at 355° continuous take-up of fabric and periodic let-off mechanism was used. Fig. 1 illustrates the shed timing of the loom, obtained from measurement.

The specifications of the weave and the warp yarns used to produce the fabric in warp tension simulation were Twill (2/2), 170 cm wide, 20 picks/cm (50 Tex worsted) and 20 ends/cm (2x55 Tex worsted).

Fig.1 The shed height variations versus loom degree, obtained, for a twill(2/2) weave

3. Modelling and Simulating the Weaving Loom

To simulate the warp tension during weaving, a mathematical model of the weaving machine warp/cloth system was developed. This system consists of the warp ends, warp beam, back rail system, heald shaft and take-up system shown in Fig. 2.

In this figure:

$L10$ and $L1$: Initial and new length of warp ends between cloth fell and heald shaft

$L20$ and $L2$: Initial and new length of warp ends between back rail and heald shaft

$L30$ and $L3$: Initial and new length of warp ends between back rail and warp beam

$Lw0$ and Lw : Initial and new length of warp ends, contacting the back rail

It is noted that the warp lengths of $L2$, $L3$ and Lw and their initial values can be calculated from the geometry of the modelled machine in Fig. 2.

$UX0$ and UX : Initial and new length of the back rail spring

α : The angle between the back rail arm and the vertical axis

$\beta1$: The angle between the warp end ($L2$) and horizontal axis

ψ : The angle between the back rail spring and the upper back rail arm

y : The displacement of the heald shaft

r : The radius of the back rail, and
 R : The radius of the warp beam.

Fig. 2 The profile of Projectile Loom, used in computer simulation

4. The Equation of the Yarn Tension

During shed forming, weft beat-up, warp let-off and fabric take-up, warp tension is changing. In addition to warp tension, the term of other forces such as spring force of the back rail, weight of back rail and friction forces are considered in the simulation.

In determining the equation of warp tension a few assumptions should be made which are concerned with the mechanical behaviour of yarns and elastic modulus of yarn when they are stretched. In the present work it is assumed that the yarns follow the Hooke's law, i.e. the tension variation of yarns have a linear relation with the elongation of the yarns. It is also assumed that there is no difference between static and dynamic elastic moduli of the yarns.

To calculate the warp tension, the whole yarn elongation was determined from the geometry of the loom and the path of warp yarns from warp beam to beat-up zone. Also the length of yarns supplied by warp let-off and the fabric length, taken-up by take-up rollers were considered in calculations. The let-off decreases the tension in the yarn, whereas fabric take-up increases the warp tension.

Heald shaft motion and its equation, during moving upward and downward, was determined in two different ways and similar sinusoidal curves were observed. To obtain the velocity equation of heald shaft, from displacement equation of the heald shaft differential was taken with respect the time, t .

We know there are following relationships between tension, elasticity modulus and elongation of a yarn [1]:

$$T = T_0 + E_y \times \frac{l - l_0}{l_0} \quad (1)$$

$$T = T_0 + E_y \times \frac{dl}{l_0} \quad (2)$$

$$\text{and } T = T_0 + dT \quad (3)$$

and consequently

$$dT = E_y \times \frac{dl}{l_0} \quad (4)$$

where, T is the warp tension at $t = t_0 + dt$, T_0 is the initial warp tension at t_0 and dT is the warp tension due to elongation of dL_t in period of dt . The amounts of L_t and dL_t can be determined from the relevant equations and the geometry of the weaving loom. E_y , which is the elastic modulus of a yarn is defined as slope of the curve of force-elongation and can be obtained [2] from equation (5). In this work, yarn modulus, E_y , was obtained about 130 cN/Tex.

$$E_y = \frac{T_f - T_i}{c(l_f - l_i) / l_i} \quad (5)$$

where T_f and T_i are the final and initial yarn tensions respectively, l_f and l_i are respectively the final and initial lengths of yarn and c is the yarn count.

5. Calculation of the Length of Warp Ends and its Variations

To calculate the warp tension, it is necessary to calculate the change of the length of warp ends. The warp end length in different parts of the loom has been specified in Fig. 2 as $L1$, $L2$, $L3$ and Lw . Their initial lengths ($L10$, $L20$, $L30$ and $Lw0$) have been measured in the static state of the loom. These lengths and their variations can be determined through geometry of the machine and their derivations. Also L_t (Total length of warp end from warp beam to cloth fell) and its derivation is obtained from equations (6) and (7).

$$L_t = L1 + L2 + L3 + Lw + L_{let} - L_{tu} \quad (6)$$

$$dL_t = dL1 + dL2 + dL3 + dLw - dL_{let} + dL_{tu} \quad (7)$$

where L_{let} is the amount (length) of yarn is let-off from warp beam and L_{tu} is the length of fabric is taken up by take-up rollers. $L2$, $L3$, Lw , L_{let} , L_{tu} can be determined from geometry and specifications of the loom.

6. Length of Warp Ends in Different Parts of Warp Sheet

As mentioned earlier to calculate the warp tension in each zone (part) of the warp, the length of warp ends in that part and its variation should be determined. Therefore in this section, the equations to determine $L1$, $L2$, $L3$ and Lw as well as their variations would be given.

Part of warp tension variation is due to shedding and beat-up which create a cyclical change in the length of warp ends.

To determine the length of warp ends between heald shaft and cloth fell, two separate states are considered.

1) The length of warp ends, as shown in Fig.3, will change sharply during beat-up, that consequently leads to sudden change in warp tension.

As can be seen, unlike other parts of warp ends, the lengths of $L1$ and $L10$ are rapidly changing during beat-up. When the cloth fell is pushed forward by the reed during beat-up, the distance between heald shaft and cloth fell, $L10$, will be:

$$L10 = d + cfd \quad (8)$$

where, $cf d$ is the cloth fell displacement during beat-up and $d=160$ (mm) is the distance between the heald shaft and cloth fell when beat-up does not happen. It is noted that $cf d$ is a function of time which will be determined later. Therefore, the warp length between heald shaft and the cloth fell, i.e. $L1$, and its variations, $dL1$, during beat-up, are obtained from equations (9) and (10)

$$L1 = [(160 + cf d)^2 + y^2]^{0.5} \quad (9)$$

$$dL1 = [(160 + cf d) \cdot d(cf d) + y \cdot dy] / L1 \quad (10)$$

where y is the position of the heald shaft respect to level of warp sheet at cloth fell position and dy is its variation.

Fig. 3. The length variations of warp ends between heald shaft and cloth fell during beat-up

II) When the beat-up does not occur, cloth fell displacement ($cf d$) is zero. Thus, considering Fig. 2 and Fig. 3, the warp ends between the heald shaft and cloth fell and its variation can be obtained from equation (11)

$$L1 = (L10^2 + y^2)^{0.5} \quad (11)$$

$$dL1 = y \cdot dy / L1 \quad (12)$$

It is also necessary to determine $L2$, $L3$, Lw and their variations, which can be obtained by considering Fig.2 and from following equations:

$$L2 = ((y + MS + MC \cdot \sin \alpha)^2 + (MK + MC \cdot \cos \alpha)^2 - r^2)^{0.5} \quad (13)$$

$$dL2 = [(y + MS + MC \cdot \sin \alpha)(dy + MC \cdot \cos \alpha \cdot d\alpha) + (MK + MC \cdot \cos \alpha)(-MC \cdot \sin \alpha \cdot d\alpha)] / L2 \quad (14)$$

$$L3 = \frac{E - (R - r) \cdot \cos \beta 2}{\sin \beta 2} \quad (15)$$

$$dL3 = \frac{(R - r - E \cdot \cos \beta 2) \cdot d\beta 2 + \sin \beta 2 \cdot dE}{\sin^2 \beta 2} \quad (16)$$

where,

$$E = MC \cdot \cos \alpha - GO$$

$$dE = -MC \cdot \sin \alpha \cdot d\alpha$$

$$Lw = r \left(\frac{\pi}{2} - \beta 1 + \beta 2 \right) \quad (17)$$

$$dLw = r(d\beta 2 - d\beta 1) \quad (18)$$

The extent of elongation in length of warp ends, wrapped around the back rail and under tension shown schematically in Fig.4, can be obtained through equation (19)[3]:

Fig. 4. The wrapped warp ends and the warp tensions at two sides of the back rail

$$dLw_e = \frac{T2 - T3}{btE} \cdot \frac{r}{\mu} \quad (19)$$

The above equation is applied for a belt with thickness of t and width of b , whereas for yarns no cross-section is assumed. Consequently, equation (19) can be modified as follows for the yarn:

$$dLw_e = \frac{T2 - T3}{E_y} \cdot \frac{r}{\mu}$$

where, dLw_e is elongation of the wrapped warp ends of Lw and since $T3 = T2 \cdot e^{-\mu \phi}$:

$$dLw_e = \frac{T2(1 - e^{-\mu \phi})}{E_y} \cdot \frac{r}{\mu} \quad (20)$$

and μ is the friction coefficient between the warp yarns and back rail, which was measured using the capstan equation.

7. Modification of Pure Elongation of Warp Ends and Warp Tension Variations

If $\mu = 0$ is assumed, the warp tension would be identical in different parts of warp length, which can be obtained from equations (3) and (4). But as we know, due to this fact that $\mu \neq 0$, the warp tension in different parts is not equal. For instance the warp tension $T2 > T3$. To determine the warp tension in different zones of warp ends such as $L2$, it is necessary to calculate the pure elongation of the above mentioned part. If the value of warp tension in this zone is calculated from:

$$dT2 = E_y \cdot \frac{dL1 + dL2}{L1 + L2} \quad (\text{Warp tension in zones of } L2$$

and $L1$ has been assumed $T2$ and its variations $dT2$)

It can be clearly seen from Fig. 2 and Fig.5 that $dL1$ and $dL2$ are not a pure elongation but also it consists of some warp ends slipped from $L3$ to this part. Therefore, it is essential to determine the pure elongation of $L1 + L2$, i.e. dLe . Calculation of dLe from geometry of the loom was difficult, thus it was tried to determine it indirectly.

Fig. 5. The geometrical variations in length of warp yarns

It is obvious that the warp tension variations above the back rail, $dT2$, can be calculated from equation (21):

$$dT2 = E_y \cdot \frac{dLe}{L1 + L2} \quad (21)$$

and regarding Fig. 5:

$$dLe = dLt - dLe3 - dLwe \quad (22)$$

Also $dT3 = E_y \cdot \frac{dLe3}{L3}$, then

$$dLe3 = L3 \cdot \frac{dT3}{E_y} \quad (23)$$

As $T3 < T2$:

$$T3 = T2 \cdot e^{-\mu\phi}, \text{ and}$$

$$\begin{aligned} dT3 &= e^{-\mu\phi} \cdot dT2 - \mu \cdot e^{-\mu\phi} T2 \cdot d\phi \\ &= e^{-\mu\phi} \cdot dT2 - \mu T3 \cdot d\phi \end{aligned} \quad (24)$$

Therefore,

$$dLe3 = L3 \cdot \frac{(e^{-\mu\phi} \cdot dT2 - \mu \cdot T3 \cdot d\phi)}{E_y} \quad (25)$$

If $dLe3$ and $dLwe$ are substituted in equation (22):

$$dLe = dLt - \frac{L3(e^{-\mu\phi} \cdot dT2 - \mu \cdot T3 \cdot d\phi)}{E_y} - \frac{(T2 - T3)r}{E_y \cdot \mu}$$

Substituting dLe in equation (21):

$$\begin{aligned} dT2 &= \frac{E_y}{(L1 + L2)} \left(dLt - \frac{L3(e^{-\mu\phi} \cdot dT2 - \mu \cdot T3 \cdot d\phi)}{E_y} \right. \\ &\quad \left. - \frac{(T2 - T3)r}{\mu E_y} \right) \end{aligned}$$

$$dT2 = \frac{1}{(L1 + L2 + L3 \cdot e^{-\mu\phi})} \cdot (E_y \cdot dLt + \mu \cdot L3 \cdot T3 \cdot d\phi - (L1 + L2)(T2 - T3)r / \mu)$$

or

$$dT2 = \frac{E_y \cdot dLt + L3 \mu \cdot T3 \cdot d\phi - (L1 + L2)(T2 - T3)r / \mu}{L1 + L2 + L3 \cdot e^{-\mu\phi}}$$

Substituting $T2 = T3 e^{\mu\phi}$ in $dT2$:

$$dT2 = \frac{E_y \cdot dLt + (L3 \mu \cdot d\phi - (L1 + L2)(e^{\mu\phi} - 1)r / \mu) T3}{L1 + L2 + L3 \cdot e^{-\mu\phi}} \quad (26)$$

8. Determining Warp Beam Rotation

As mentioned earlier, the extent of warp beam rotation, α , should be determined from the dynamic equations of system. To calculate α , the free body diagram of the forces, which acting on the back rail, are drawn, as illustrated in Fig. 6.

Fig. 6. Free diagram of forces acting on the back rail

The angular acceleration of the back rail, $\frac{d^2\alpha}{dt^2}$, can be obtained from equation (27):

$$\tau = \sum M_M = I_b \times \frac{d^2\alpha}{dt^2} \quad (27)$$

or

$$\frac{d^2\alpha}{dt^2} = \frac{\sum M_M}{I_b}$$

where τ , is the torque, which is equal to $\sum M_M$ (the sum of moments of forces). If this is replaced by its components, we have:

$$\begin{aligned} \frac{d^2\alpha}{dt^2} &= [(T2 \cdot \sin(\alpha - \beta 1) + T3 \cdot \cos(\beta 2 - \alpha) + W \cdot \cos \alpha) \cdot MC - \\ &\quad (T2 - T3) \cdot r - F_s \cdot MX \cdot \sin \psi] / I_b \end{aligned}$$

where:

$T2$ and $T3$ are warp tensions in zones of $L2$ and $L3$ of the warp ends respectively,

W is the weight of the back-rail (shown in Fig. 7),

Fig. 7. The main view of back-rail roll

MC is the length of the lever connecting back-rail to pivot M ,

MX is the lever whose end is connected to pivot M and its other end is linked to the spring

F_s , is spring force and

I_b is the moment of inertia (Back rail) about pivot of back rail (point M), which can be obtained using formula (28):

$$I_b = \frac{l}{2} \rho \cdot \pi \cdot L_m (r_o^4 - r_i^4) + 2 \times \frac{l}{2} \cdot \rho \cdot \pi \cdot L_l \cdot r_l^4 + M_b \cdot MO^2 \quad (28)$$

where r_o and r_i are outer and inner radius of the main roll of back rail, L_m is the length of the main roll of back rail, r_l and L_l are radius and the length of two levers of the back rail, M_b is mass of the back rail.

9. Results

In order to solve the equations of tension, angular velocity, and angular acceleration it is essential to integrate them numerically using the Runge-Kutta method [4 -6], starting from the initial values of warp tension T_0 , angle α_0 , and angular velocity $\dot{\alpha}_0$ of the back rail, which were measured.

In this section the traces of warp tension, back rail position and the angular velocity of the back rail obtained from simulation and measurement, are displayed.

By running a computer programme (written in FORTRAN) for warp tension simulation, the required data were produced and saved in a data file. Then the graph of warp tension vs. time (sec.), whose data was obtained from calculation, was plotted, as shown in Fig. 8.

When both let-off and take up are assumed continuous, the equations (9) and (10) should be modified as follows:

$$L_i = L1 + L2 + L3 + Lw \quad (29)$$

$$dL_i = dL1 + dL2 + dL3 + dLw \quad (30)$$

The calculated warp tension variation was compared with that obtained by actual measurement using a shell gauge [7], [8]. The shell gauge is a tension meter having two strain gauges, which have been fixed at two sides of a spring U-shape shell, made of brass. The strain gauges, which are in fact two variable resistors, form a Whetstone bridge in combination with two similar resistors. Fig. 9 shows the trace obtained from warp tension measurement, carried out on the weaving loom. The data captured from the signal of tension meter, were processed using Digital Signal Processing (DSP). It is added that the number of data was adjusted 512 data/cycle of weaving.

Also the displacement of the back rail during weaving, obtained from calculation, was plotted vs. time, as shown in Fig. 10.

As mentioned before, the position of back rail is specified by its angle respect to vertical axis, i.e. α , which is stated in radian. The measurement of the back rail oscillations

Fig. 8 Warp tension variations vs. Time (sec.), obtained by calculation

Fig. 9. Warp tension variations vs. Time (sec.), measured by shell gauge tension meter

Fig. 10. The back rail displacement during weaving, obtained by calculation

was carried out using a laser based displacement transducer [9] together with a proximity detector [10] being used to provide a trace of reed position. The displacement transducer used has a working distance of 20 ± 1 mm. Therefore, it was mounted under one of the back rail arms on a rigid support. Fig. 11 illustrates the back rail oscillations and the reed motion.

Fig. 11. Back rail oscillation (locked back rail), A: Back rail oscillation, B: Reed motion

Fig.12. Cloth fell displacement, cfd vs. loom degree

10. Discussion and Conclusions

Comparing the warp tension traces obtained by two methods, Fig.8 and Fig.9, show a good agreement between the results, although the warp tension, measured by the tension meter, has some fluctuations. The reason for this can be relevant to the vibrations of different parts of the loom, which cannot easily be modelled in simulation.

To examine the form of reed motion, initially it was attempted to record the displacement of the cloth fell displacement during beat-up by an electro-optic proximity detector. The curve of the reed motion could be considered as a sinusoidal curve but this attempt was not successful, since this instrument did not behave linearly. Thus its trace could not be used to determine the equation of cloth fell displacement (cfd). Therefore, it was decided to record the cloth fell displacement, cfd , during the beat-up using a high-speed camera at 1000 frames/sec. The beat-up starts from 42 degrees and ends around 58 degrees. It should be noted that due to loom vibrations, during the beat-up, the pictures taken by the high-speed camera were not quite clear which somewhat affected the reading by the analyser. Another problem was that due to the reed obscuring the cloth fell during the beat up that caused the camera could not be positioned vertically. So, it was placed at a slight angle to the vertical line.

To plot the reed movement during beat-up, the movements measured on the analyser was converted to their actual values to produce the curve shown in Fig. 12.

It can be seen that the movement is not a sinusoidal curve. Therefore it may be concluded that if it was possible to determine the actual equation of cfd from its trace, the warp tension trace obtained from calculation would be more similar to the trace measured by the tension meter. From this figure, it also could be observed that beyond the beat-up period, the cloth fell is fluctuating, whereas it was ignored in modelling and simulation. As it is obvious, the beat-up is done impulsively, therefore it is difficult to be modelled. What mentioned about the beat-up curve may be true for the heald shaft motion that was assumed to move sinusoidally. Another point about cfd , Fig.12, concerns the position of cloth fell when the beat-up terminates.

Comparison of the back rail movements, obtained from calculation and measurement, Fig.10 and Fig.11 respectively, indicates a general agreement between two traces. The amplitudes of the back rail movement in both cases are nearly the same, however the amplitude of the back rail fluctuation, measured by L.V.D.T (Linear Voltage Differential Transformer transducer) is slightly higher which can result from the inaccuracy of the instrument and the measurement. The other difference between the two curves, is the presence of vibrations in the curve obtained from measurement, which can be justified as explained earlier about the warp tension curve.

Therefore, it may be concluded that the curves obtained from calculations can satisfactorily represent the measured curves. The calculated curves also can get more close to the measured traces if other assumptions such as linearity of elasticity of the warp ends etc. are modified. Since the yarns may not quite follow the Hooke's law i.e. their behaviour is more complicated than what was assumed. As mentioned before, the same modifications can be applied for the heald shaft motion and the cloth fell displacement, which were assumed to be sinusoidal functions. Other source of difference between the results may be errors of the initial values and boundary conditions in solving the system of differential equations.

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