

Study on the Dynamic Characteristics of Warp in the Process of Weaving

College of Electromechanical Engineering,
Xi'an Polytechnic University,
Xi'an, 710048, P.R.China;
E-mail:dfshen@xpu.edu.cn

*College of Mechanical Engineering,
Dong Hua University,
Shanghai 201620, P.R.China

Abstract

The fluctuation process of warp movement is analysed by the nonlinear vibration method. Based on Newton's Law, a differential equation of warp axial/cross direction movement is established. This paper separates the time variable from the space variable by the variable-separating method, then it gives a numerical solution of the motion equation by the fourth-order Runge-Kutta method. Also this paper discusses influencing factors and variable trends for warp vibration. Finally a method for the control of vibration is introduced.

Key words: loom, warp, nonlinear vibration, L-P method, Mathieu equation.

Introduction

The spindle speed of a shuttle-less loom is much higher than that of a shuttle loom. The warp seesaws with high frequency and is subject to impact loads (such as drawing tension, friction, air-resistance, inertia force and so on) during loom running. Theoretical analysis and experimental results show that the warp has tiny vibration when it is moving in the axis, affecting warp tension and distortion [1 - 3]. The vibration will cause friction between warps, tear the starch film, reduce the warp's breaking strength and even break the warp. Although many researchers have investigated nonlinear vibration, few have studied warp vibration [4, 5]. The tiny vibration is nonlinear, and its amplitude and frequency were difficult to measure and calculate. This paper takes warp vibration in the weaving process as the research subject. The assumption is that the cross sections of yarns are round [6]. Based on Newton's Law and the nonlinear method, the effects of yarn parameters on transverse vibration were discussed.

Basic warp model

Warp vibration may be divided into in-plane vibration and out-plane vibration [7]. Warp will undergo out-plane vibration when the excitation frequency is changed discontinuously or the response amplitude is greater than the critical value. Research shows that the amplitude and frequency of out-plane vibration are the subsets of in-plane vibration [8].

To simplify research and reflect the essence of the problem, only in-plane vibration is discussed. The basic assumptions are as follows:

1. Flexural rigidity, torsional stiffness and shear stiffness are not taken into account.
2. The Cross-section which is vertical to the warp axes before deformation will still be vertical to the warp axes after deformation.
3. The deformation constitutive relation of the warp to obey Hooke's law and the force at each point is equal.

In **Figure 1**, the mass of the warp fragment is $dm = \rho \Delta y$. F, G, F', and G' represent two non-deformed endpoints and two deformed endpoints, respectively.

The displacement of point F is:

$$\Delta F = u(y, t)i + v(y, t)j \quad (1)$$

The displacement of point G is:

$$\Delta G = \left(u + \frac{\partial u}{\partial y} dy\right)i + \left(v + \frac{\partial v}{\partial y} dy\right)j \quad (2)$$

From **Figure 1**, we can obtain:

$$\Delta F + \Delta F'G' = \Delta G + dy \cdot j$$

where $\Delta F'G'$ is the position vector, whose point G' is relative to point F'.

The small unit length deformed is given by **Equation 3**:

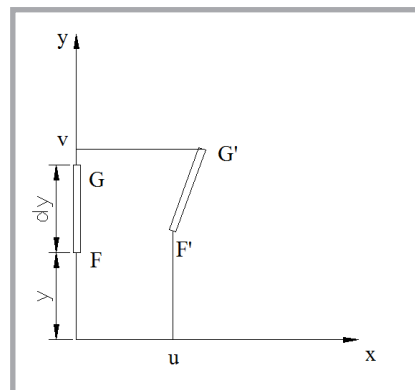


Figure 1. Model of a short fragment of warp.

$$|\Delta F'G'| = ds = \left[\left(1 + \frac{\partial v}{\partial y}\right)^2 + \left(\frac{\partial u}{\partial y}\right)^2 \right]^{\frac{1}{2}} dy \quad (3)$$

The warp strain generated by transverse elongation is shown in **Equation 4**:

$$\varepsilon = \frac{ds - dy}{dy} = \left[\left(1 + \frac{\partial v}{\partial y}\right)^2 + \left(\frac{\partial u}{\partial y}\right)^2 \right]^{\frac{1}{2}} - 1 \approx \frac{\partial v}{\partial y} + \frac{1}{2} \left(\frac{\partial u}{\partial y}\right)^2 \quad (4)$$

Yarn is a type of viscoelastic material. Different materials of yarn have different constitutive relations. For the purpose of this computation, a simple Kelvin model is proposed to analyse the warp's vibration equation [9]. The stress-strain relationship of the warp is:

$$\sigma = E\varepsilon + \eta \frac{d\varepsilon}{dt} = E'\varepsilon(y, t) \quad (5)$$

Where:

E is the warp's stiffness coefficient, E' the young's modulus of elasticity, η the viscosity damping coefficient.

Mathematic model of warp vibration

Warp can be divided into four areas based on its position during the weaving process, as shown in **Figure 2**.

Area I: The segment between the beam and back rest, in which warp motion belongs to an axial movement with two ends fixed, with transverse vibration taking place.

Area II: The segment is between the back rest and drop wires. The warp motion is the same as in Area I.

Area III: The segment between the drop wires and heald frame, in which the shed

is formed by alternating heald frames. Warp motion belongs to an axial movement with one end fixed. The warps not only withstand the axial force but also the periodic radial force.

Area IV: The segment is between the heald frame and fell of cloth. The warp motion is the same as in Area III.

The warp is fully drawn during the shedding process. The warp motion in the shed is actually treated as a two part superposition: firstly the warp moves up and down by a shedding operation in a steady motion; secondly the warp makes a tiny vibration based on its steady motion. The tiny vibration can also be divided into two categories: the longitudinal vibration along the warp axis and the transverse vibration perpendicular thereto. This paper mainly analyses the tiny vibration. This vibration analysis may refer to string vibration. A common way

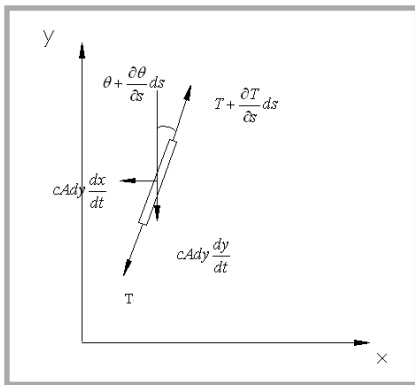


Figure 3. Force schematic of small warp fragments.

is to transform it into two ends fixed with boundary conditions and to solve these partial differential equations, which converts the displacement form with one end fixed into an inner tension change with two ends fixed. Thus through the change from displacement to tension, the string vibration analysis with one end moved may translate into a string inner tension change with two ends fixed. Therefore the warp vibration analysis in the shedding area translates into a moving string with both ends fixed, being similar to the warp vibration in Area I, and II. Here the warp in Area I is analysed, for example.

In **Figure 3**, the warp's initial tension is T_0 . The warp's length will change while it is moving. Hence the inner tension of the warp will also change. The instan-

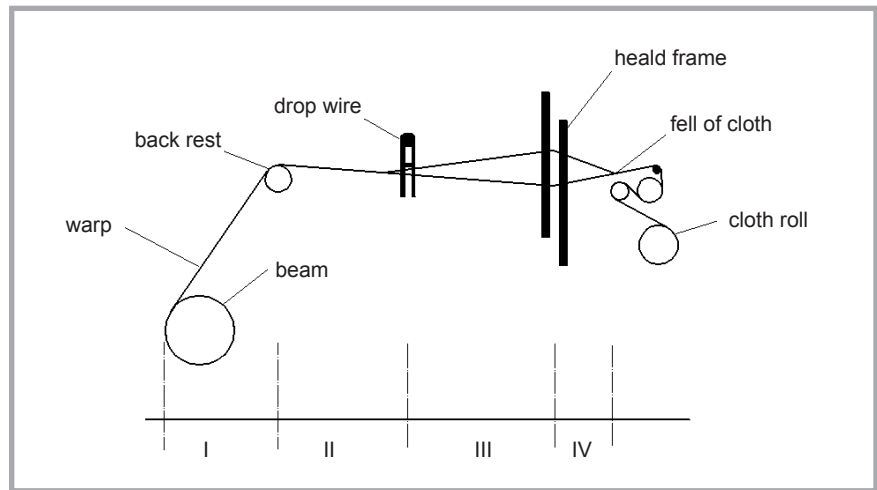


Figure 2. Schematic diagram of warp movement.

aneous value of tension is expressed as [10]:

$$T = T_0 + \frac{E' A (ds - dy)}{dy} = T_0 + E' \varepsilon(y, t) A \quad (6)$$

Let the damping coefficient of the warp's unit volume be c . Assuming the linear damping force is proportional to the absolute velocity V of any point in the warp, the damping force of a small warp fragment is $c A d y \frac{dy}{dt}$ and $c A d y \frac{dx}{dt}$.

According to Newton's law of motion the dynamic equations of warp can be formulated as the set of **Equations 7**.

In general, the trigonometric function is expanded by a second-order Taylor's algorithm, where $\sin \theta \approx \theta$, $\cos \theta \approx 1 - \frac{1}{2} \theta^2$.

Substitute them into **Equation 7** and eliminate higher order terms, the vibration equations which only contain an unknown displacement are as presented in **Equation 8**.

The warp boundary conditions are:

$$u(0, t) = 0, u(L, t) = 0 \quad (9)$$

where L is the warp's dynamic length from the beam to back rest.

$$\begin{cases} \left(T + \frac{\partial T}{\partial s} ds \right) \sin \left(\theta + \frac{\partial \theta}{\partial s} ds \right) - T \sin \theta - c A d y \frac{dx}{dt} = \rho A d y \frac{d^2 x}{dt^2} \\ \left(T + \frac{\partial T}{\partial s} ds \right) \cos \left(\theta + \frac{\partial \theta}{\partial s} ds \right) - T \cos \theta - c A d y \frac{dy}{dt} = \rho A d y \frac{d^2 y}{dt^2} \end{cases} \quad (7)$$

$$\begin{cases} \rho \frac{\partial^2 v}{\partial t^2} + 2 \rho V \frac{\partial^2 v}{\partial t \partial y} + \rho V^2 \frac{\partial^2 v}{\partial y^2} = \frac{\partial(E \varepsilon)}{\partial y} - \left(\frac{T_0}{A} + E \varepsilon \right) \frac{\partial u}{\partial y} \frac{\partial^2 u}{\partial y^2} - \frac{1}{2} \left(\frac{\partial u}{\partial y} \right)^2 \frac{\partial(E \varepsilon)}{\partial y} - c \left(V + V \frac{\partial v}{\partial y} + \frac{\partial v}{\partial t} \right) \\ \rho \frac{\partial^2 u}{\partial t^2} + 2 \rho V \frac{\partial^2 u}{\partial t \partial y} + \left(\rho V^2 - \frac{T_0}{A} \right) \frac{\partial^2 u}{\partial y^2} = \frac{\partial u}{\partial y} \frac{\partial(E \varepsilon)}{\partial y} + E \varepsilon \left(\frac{\partial u}{\partial y} \right)^2 - c \left(V \frac{\partial u}{\partial y} + \frac{\partial u}{\partial t} \right) \end{cases} \quad (8)$$

$$\begin{aligned} & \rho \frac{\partial^2 u}{\partial t^2} + 2 \rho V \frac{\partial^2 u}{\partial t \partial y} + \left(\rho V^2 - \frac{T_0 + T_1 \cos \Omega t}{A} \right) \frac{\partial^2 u}{\partial y^2} = \\ & = \frac{3}{2} E_0 \left(\frac{\partial u}{\partial y} \right)^2 \frac{\partial^2 u}{\partial y^2} + 2 \eta \frac{\partial u}{\partial y} \frac{\partial^2 u}{\partial t \partial y} \frac{\partial^2 u}{\partial y^2} + \eta \left(\frac{\partial u}{\partial y} \right)^2 \frac{\partial^2 u}{\partial y^2} \frac{\partial u}{\partial t} - c \left(\frac{\partial u}{\partial y} V + \frac{\partial u}{\partial t} \right) \end{aligned} \quad (10)$$

$$\begin{aligned} & \frac{\partial^2 u}{\partial t^2} + 2 \gamma \frac{\partial^2 u}{\partial t \partial y} + \left(\gamma^2 - 1 - a \cos \omega t \right) \frac{\partial^2 u}{\partial y^2} + c_1 \frac{\partial u}{\partial y} + c_2 \frac{\partial u}{\partial t} + \\ & - \frac{3}{2} E_e \left(\frac{\partial u}{\partial y} \right)^2 \frac{\partial^2 u}{\partial y^2} - 2 E_v \frac{\partial u}{\partial y} \frac{\partial^2 u}{\partial t \partial y} \frac{\partial^2 u}{\partial y^2} - E_v \left(\frac{\partial u}{\partial y} \right)^2 \frac{\partial^2 u}{\partial y^2} \frac{\partial u}{\partial t} = 0 \end{aligned} \quad (12)$$

where

$$\gamma = V \sqrt{\frac{\rho A}{T_0}}, a = \frac{T_1}{T_0}, \omega = \Omega \sqrt{\frac{\rho A L^2}{T_0}}, E_e = \frac{E_0 A}{T_0}, E_v = \eta \sqrt{\frac{A}{\rho T_0 L^2}}, c_1 = \frac{A L c V}{T_0}, c_2 = c \sqrt{\frac{A}{T_0 \rho}}$$

Equations 7, 8, 10 and 12.

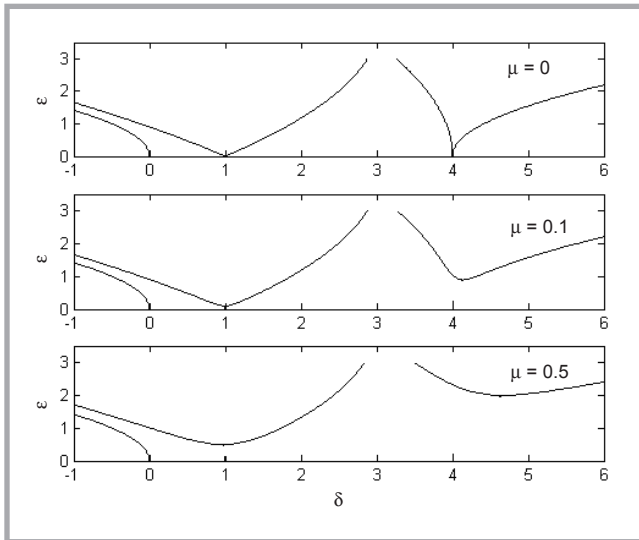


Figure 4. System stability chart with various values of damping coefficient μ .

$$\delta_0 = 1 \quad (17)$$

When $\delta_0 = 1$, the boundary equation is:

$$\delta = 1 \pm \sqrt{\varepsilon^2 - \mu^2} - \frac{1}{8}\varepsilon^2 \quad (18)$$

When $\delta_0 = 4$, the boundary equation is:

$$\delta = 4 + \frac{1}{6}\varepsilon^2 \pm \sqrt{\frac{1}{16}\varepsilon^4 - 4\mu^2} \quad (19)$$

In **Figure 4**, the area above the curve is an unsteady area, where the transverse vibration amplitude of the warp tends to rise, whereas the area below the curve is a steady area, where the transverse vibration amplitude of the warp tends to fall; and the area on the curve is the transition zone, where the transverse vibration amplitude of the warp is nearly constant. **Figure 4** shows that linear damping can reduce the unsteady area. In practice, only the biggest unsteady area is considered. Here, with $\delta = 1$, the dynamical property of the warp is forecast as **Figure 4**.

At a particular point $\delta=1$, when damping does not affect the warp, with even the tension fluctuation of the warp being tiny, the parameter resonance of the warp will also happen; when damping affects the warp, if ε ($\varepsilon = 2\pi^2/\omega^2$) is less than that of the corresponding value on the transition curve $\delta = 1$, the warp's dynamic characteristic will be in a steady area, with its amplitude of transverse vibration tending to fall.

When the damping coefficient $\mu > 0$, the unsteady area reduces relative to $\mu = 0$. The larger the damping, the less the energy loss. Hence the kinetic energy that is transferred to the warp decreases, and the warp tension fluctuation decreases.

In an unsteady area, because damping exists, the excitation parameter ε requires an increase. Damping may reduce the dynamic unsteady area, although it cannot restrain the response of the parametric resonance from growing infinitely. In general, the effect of damping restraining amplitude is ignored with an increase in the incentive amplitude, with non-linear factors of the warp playing a more and more important role.

It can be observed from the definition of δ and ε that while the material of the warp remains unchanged, the influence factors of the stable region are the warp velocity, ratio of tension fluctuation, angular velocity of tension fluctuation and the length of the warp vibration region.

Nonlinear perturbation analysis of transverse vibration

In general, the natural frequency of longitudinal vibration is much larger than that of transverse vibration. Therefore the transverse vibration of warp should be especially studied. Here substitute $\varepsilon = \frac{1}{2}u_y^2$ into **Equation 8**. Tension has a cyclical change during loom operation, and T_0 is replaced by $T_0 + T_1 \cos \Omega t$. Accurate to cubic nonlinearity term as **Equation 10**.

Introducing the following dimensionless variables:

$$v^* = \frac{v}{L}, u^* = \frac{u}{L}, y^* = \frac{y}{L}, t^* = t \sqrt{\frac{T_0}{\rho h^2}} \quad (11)$$

Substituting **Equation 11** into **Equation 10** and omitting *, the dimensionless equation of transverse vibration is presented in **Equation 12**.

Considering the boundary conditions (**Equation 9**), the solutions of differential **Equation 12** have the following form

$$u(y, t) = \sum_{n=1}^{\infty} q_n(t) \sin\left(\frac{n\pi}{L}y\right) \quad (13)$$

Here, the first mode is emphasised in the analysis. The differential equation of dimensionless transverse vibration is obtained by substituting $u(y, t)$ into **Equation 12** obtaining **Equation 14**:

$$\ddot{q}_1 + c2\dot{q}_1 + \frac{3}{4}E_c\left(\frac{\pi}{L}\right)^4 q_1^2 \dot{q}_1 - \left(\frac{\pi}{L}\right)^2 (\gamma^2 - 1 + a \cos \omega t) q_1 + \frac{3}{8}E_c\left(\frac{\pi}{L}\right)^2 q_1^3 = 0 \quad (14)$$

Because the warp's initial tension is larger, the nonlinear effect of the second

item will disappear [11]. **Equation 14** is rewritten as **Equation 15**:

$$\ddot{q}_1 + c2\dot{q}_1 + \left(\frac{\pi}{L}\right)^2 (1 - \gamma^2 + a \cos \omega t) q_1 + \frac{3}{8}E_c\left(\frac{\pi}{L}\right)^2 q_1^3 = 0 \quad (15)$$

In practice, the tension fluctuation ratio $a \ll 1$. Hence the basic problem of warp vibration will be attributed to the generalized Mathieu equation of nonlinear vibration in **Equation 15**, which can be solved by the perturbation method. Cyclical fluctuation parameters appear in the stiffness item. Let $\mu = c2$,

$$\delta = 4\left(\frac{\pi}{L}\right)^2 (1 - \gamma^2) \pi^2 / \omega^2, \varepsilon = 2\left(\frac{\pi}{L}\right)^2 a \pi^2 / \omega^2,$$

$$C_3 = \frac{3}{8}E_c\left(\frac{\pi}{L}\right)^2$$

Substitute them into **Equation 15**:

$$\ddot{q}_1 + \mu \dot{q}_1 + (\delta + 2\varepsilon \cos 2t^*) q_1 + C_3 q_1^3 = 0 \quad (16)$$

where $\varepsilon < 1$.

Unlike forced vibration, the linear damping force in parametrically excited vibration cannot suppress the amplitude, only decrease the steady region. Here the uniformly valid solution of **Equation 16** is solved by the L - P method. The solution of the Mathieu equation may be steady or unsteady [12], but the point in the boundary curves $\delta(\varepsilon)$ is stable. Assuming the solution is

$$q = q_0(t) + \varepsilon q_1(t) + \varepsilon^2 q_2(t) + \dots$$

$$\delta = \delta_0 + \delta_1 + \varepsilon^2 \delta_2 + \dots$$

the result is given directly by the perturbation method [13].

When $\delta_0 = 0$, the boundary equation is:

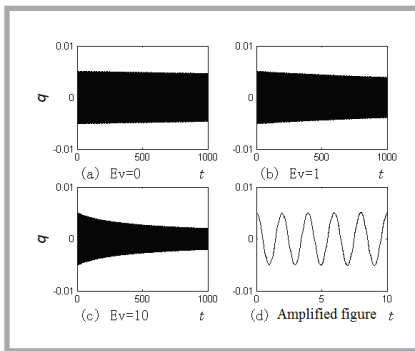


Figure 5. Effect of viscosity parameter on dynamic response.

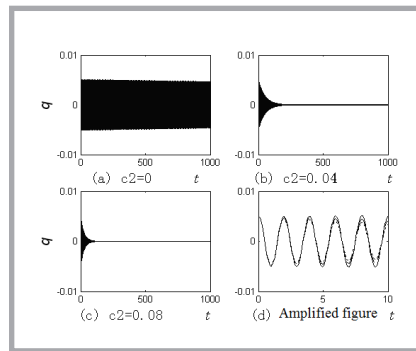


Figure 6. Effect of damping coefficient on dynamic response.

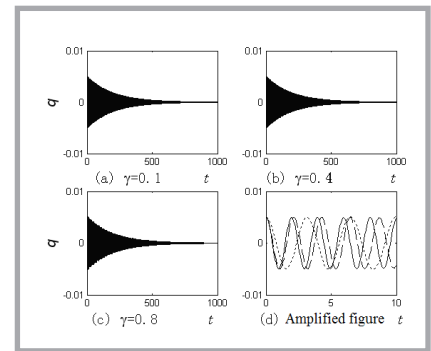


Figure 7. Effect of warp velocity on dynamic response.

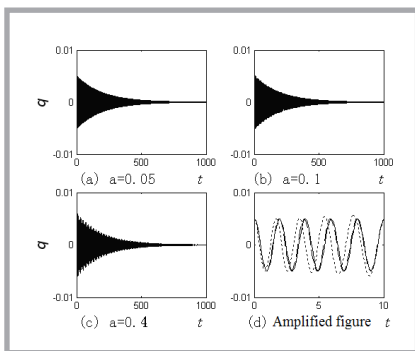


Figure 8. Effect of tension fluctuation on dynamic response.

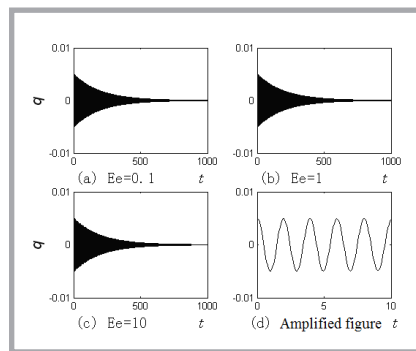


Figure 9. Effect of elastic coefficient on dynamic response.

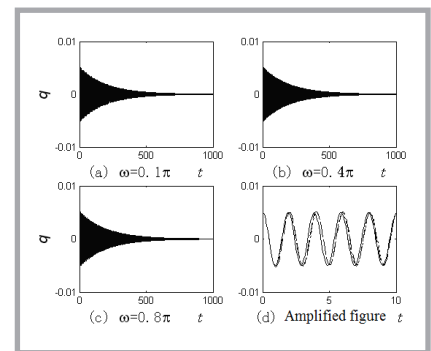


Figure 10. Effect of tension fluctuation speed on dynamic response.

Influence of various parameters on vibration with numerical analysis

The numerical results of nonlinear *Equation 14* are solved by the fourth-order *Runge-Kutta* method, and then the effects of yarn parameters on the transverse vibration of the warp are discussed. These parameters include yarn material parameters, steady-state tension and disturbance tension.

Effect of the viscosity parameter on the dynamic response

Let $c_2 = 0$, $E_e = 0.1$, $\omega = 0.1\pi$, $\gamma = 0.1$, $L = 1$, $a = 0.05$, the initial condition is $q_0 = 0.005$, $\dot{q}_0 = 0$, **Figure 5.a** $E_v = 0$, **Figure 5.b** $E_v = 1$, **Figure 5.c** $E_v = 10$, and **Figure 5.d** is the amplified frequency figure of the three curves. These figures show that as the viscosity E_v increases, the system amplitude decreases, with the dissipation ability being strengthened and the system frequency unchanged.

Effect of damping coefficient on dynamic response

Let $E_v = 0$, $E_e = 0.1$, $\omega = 0.1\pi$, $\gamma = 0.1$, $L = 1$, $a = 0.05$, the initial condition is $q_0 = 0.005$, $\dot{q}_0 = 0$, **Figure 6.a** $c_2 = 0$, **Figure 6.b** $c_2 = 0.04$, **Figure 6.c** $c_2 = 0.08$,

and **Figure 6.d** is the amplified frequency figure of the three curves. These figures show that as the damping coefficient c_2 increases, the system amplitude obviously decreases, with the dissipation ability strengthened and, system frequency unchanged.

Effect of warp velocity on dynamic response

Let $E_v = 0$, $E_e = 0.1$, $\omega = 0.1\pi$, $\gamma = 0.1$, $c_2 = 0.01$, $L = 1$, $a = 0.05$, the initial condition is $q_0 = 0.005$, $\dot{q}_0 = 0$, **Figure 7.a** $\gamma = 0.1$, **Figure 7.b** $\gamma = 0.4$, **Figure 7.c** $\gamma = 0.8$, and **Figure 7.d** is the amplified frequency figure of the three curves. These figures show that as the speed γ increases, the system frequency decreases and the system amplitude remains unchanged.

Effect of tension fluctuation on dynamic response

Let $E_v = 0$, $E_e = 0.1$, $\omega = 0.1\pi$, $\gamma = 0.1$, $c_2 = 0.01$, $L = 1$, the initial condition is $q_0 = 0.005$, $\dot{q}_0 = 0$, **Figure 8.a** $a = 0.05$, **Figure 8.b** $a = 0.1$, **Figure 8.c** $a = 0.4$, and **Figure 8.d** is the amplified frequency figure of the three curves. These figures show that as the amplitude of tension fluctuation a increases the system vibra-

tion frequency increases and the system of amplitude remains unchanged.

Effect of elastic coefficient on dynamic response

Let $a = 0.05$, $E_v = 0$, $\omega = 0.1\pi$, $\gamma = 0.1$, $c_2 = 0.01$, $L = 1$, the initial condition is $q_0 = 0.005$, $\dot{q}_0 = 0$, **Figure 9.a** $E_e = 0.05$, **Figure 9.b** $E_e = 1$, **Figure 9.c** $E_e = 10$, and **Figure 9.d** is the amplified frequency figure of the three curves. These figures show that as the elastic coefficient E_e increases, the system vibration remains unchanged.

Influence of tension fluctuation speed on dynamic response

Let $E_v = 0$, $E_e = 0.1$, $a = 0.05$, $\gamma = 0.1$, $c_2 = 0.01$, $L = 1$, the initial condition is $q_0 = 0.005$, $\dot{q}_0 = 0$, **Figure 10.a** $\omega = 0.1\pi$, **Figure 10.b** $\omega = 0.4\pi$, **Figure 10.c** $\omega = 0.8\pi$, and **Figure 10.d** is the amplified frequency figure of the three curves. These figures show that as the fluctuation speed increases, the system vibration frequency and system of amplitude basically remain unchanged.

Effect of warp length on dynamic response

Let $E_v = 0$, $E_e = 0.1$, $\omega = 0.1\pi$, $a = 0.05$, $\gamma = 0.1$, $c_2 = 0.01$, the initial condition

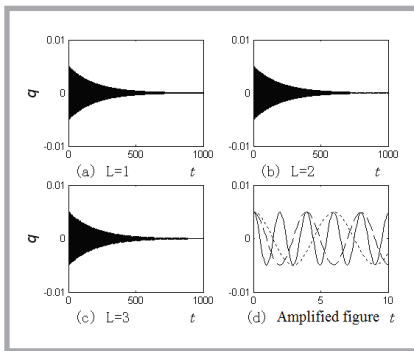


Figure 11. Effect of warp length on dynamic response.

is $q_0 = 0.005$, $\dot{q}_0 = 0$, **Figure 11.a** $L = 1$, **Figure 11.b** $L = 2$, **Figure 11.c** $L = 3$, and **Figure 11.d** is the amplified frequency figure of the three curves. These figures show that as the warp length L increases, the system vibration amplitude remains unchanged and the frequency decreases.

Effect of yarn irregularity on dynamic response

Yarn irregularity corresponds to the variable sectional area A on the vibration mathematical model. **Equation 12** indicates that the variation of the sectional area may affect E_v , ω , E_e , γ & $c2$. Because yarn irregularity is continuous and impossible to avoid, the warp vibration gets very complex, even appearing chaotic. If A increases, E_v , ω , E_e , γ & $c2$ will increase; on the other hand, if A decreases, E_v , ω , E_e , γ & $c2$ will decrease. **Table 1** shows the trends of amplitude and frequency during yarn unevenness. It can be observed that the amplitude and

Table 1. Trend of amplitude and frequency for a cross sectional area; NOTE: \uparrow - increase; \downarrow - decrease; \circ - invariant.

Item	Cross sectional area \uparrow		Cross sectional area \downarrow	
	amplitude	frequency	amplitude	frequency
E_v	\downarrow	\circ	\uparrow	\circ
ω	\circ	\circ	\circ	\circ
E_e	\circ	\circ	\circ	\circ
γ	\circ	\downarrow	\circ	\uparrow
$c2$	\downarrow	\circ	\uparrow	\circ

Table 2. Experiment data.

No. of Experiment	Item		Maximum amplitude, mm	Average amplitude, mm
1	voltage, V	1	2.30	1.61
		5	3.31	2.73
		12	4.94	3.23
2	frequency, Hz	10	2.30	1.61
		50	2.32	1.58
		200	2.32	1.60
3	length, mm	1000	2.30	1.58
		500	2.31	1.61

frequency decrease in thick places and increase in thin places.

Experiment

A stable test of a yarn's axial movement with both ends fixed is not easily performed because the fracture strength of single yarn is too low. Hence we designed an experimental apparatus to test single yarn vibration with one end fixed and the other moved. The moved end caused a change in the yarn's internal tension, similar to Area I. A schematic diagram of the experimental apparatus is shown in **Figure 12**. The apparatus fundamentally consisted of a baltimore groove, a piezoelectric patch (PZT), an optical microscope (DC500, Leica), signal generator and computer.

The baltimore groove is made of silicone material (width: 10 mm, depth: 30 mm, length: 1000 mm/500 mm). The viscosity of silicone can fix both ends of the single yarn to form a beam shape structure. PZT is fixed on the side of the groove, and the signal generator drives the PZT to vibrate in a horizontal direction, hence the yarn also vibrates. The observation direction of DC500 is vertical. Through the computer connected to the optical microscope, one can observe the amplitude variation of the single yarn. This apparatus can only measure the yarn amplitude. For the shed, loom speed, and length, three experiments were designed.

Experiment 1: both ends of the yarn are fixed, PZT is fixed on one side of the groove

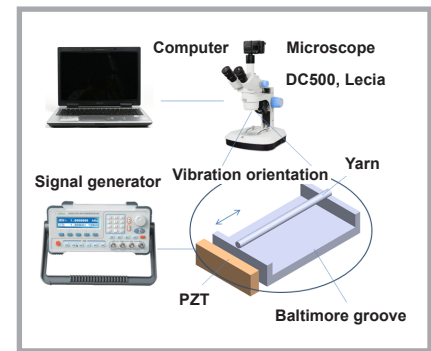


Figure 12. Experimental apparatus of warp vibration.

and only the voltage is changed (1 V, 5 V, 12 V), where yarn tension = 80 cN, PZT frequency = 10 Hz, groove length = 1000 mm, and the yarn is T65/JC35 58.3 tex.

Experiment 2: only the PZT frequency is changed (10, 50, 200 Hz), where yarn tension = 80 cN, PZT voltage = 1V, groove length = 1000 mm, and the yarn is T65/JC35 58.3 tex.

Experiment 3: only the groove length is changed (1000 mm, 500 mm), where yarn tension = 80 cN, PZT voltage = 1 V, PZT frequency = 10 Hz, and the yarn is T65/JC35 58.3 tex.

Table 2 shows that the experimental results (sampling time interval - 100 ms, the number of sampling - 1024). The amplitude changes in the experiments are in reasonable accordance with the numerical computing.

Warp vibration control

It is required to avoid the unsteady area. In the steady area, the warp should be made to produce low-frequency vibration to reduce the friction times between warps. According to **Equation 14**, when approx. $\gamma = 1$ the warp speed is approximately equal to the warp wave velocity, with an unsteady area appearing. This is the same conclusion as Swope [13]. But, in fact, the warp wave velocity is greater than warp speed. Thus the amplitude will not grow indefinitely and the warp will only vibrate in a steady area. In accordance with **Equation 15**, there are three ways to reduce the frequency of the warp vibration:

- 1) Increase the warp's linear velocity.
- 2) Increase the warp length of shed.
- 3) Reduce the tension fluctuation amplitude.

For the adjustment of the first two items, friction times of warp in a steady motion need to be considered, which will be subject to yarn quality. Therefore the first two items should not be considered as ways of adjusting the frequency. Because these factors can influence warp vibration frequency, the first two items should be considered in determining loom parameters. For the third item, it should be considered in the loom's let-off system design, and it is worth to popularize in particular application. The tension fluctuation might be influenced by the following factors when the loom rotates in a cycle: take-up speed, let-off speed, shed motion curve and beat-up curve. The beat-up and shed are the major factors in tension variation per period. Thus the two ways which adjust warp tension rapidly and reduce the warp tension peak can decrease the vibration of the warp. The methods that reduce the warp's tension fluctuation may be used in the following two ways:

- 1) Adding a let-off lever, which can reduce the tension variation peak within one revolution through back rest active moments.
- 2) Adopting an electronic let-off system with high speed response. The let-up speed is adjusted two times in one revolution, with high speed in the opening shed and low speed in the closing shed. Thus the tension will remain stable.

■ Conclusions

Based on the dynamic model of the warp moving process, through nonlinear perturbation analysis and numerical analysis, we get the following conclusions:

- 1) In the warp transverse vibration might take place, belonging to nonlinear parameter vibration.
- 2) The vibration will diffuse in the unsteady area, but an unsteady area cannot appear in the actual condition.
- 3) In certain warp material, the vibration frequency in the steady area is connected to the absolute warp speed, warp length and tension fluctuation amplitude.
- 4) Quick adjustment of warp tension is necessary to reduce warp vibration.

References

1. Lai Z. Research on the influence of shedding motion on warp weaving trait. *Silk* 2005; 6: 41-44.
2. Mei SQ. A study on the dynamic characteristics of shed warp. *Basic Sciences Journal of Textile University* 1999; 12(2): 162-165.
3. Morton WE, Hearle WS. *Physical properties of textile fibres*. The textile institute, Manchester, 1993, pp. 322-376.
4. Fumio M, Teruo W, Hideaki T, et al. Dynamic tension on yarns being unwound from a beam. *Journal of the Textile Machinery Society of Japan* 1979; 125(4): 93-99.
5. Clark JD, Fraser WB, Stump DM. Modeling of tension in yarn package unwinding. *Journal of Engineering Mathematics* 2001; 140(1): 59-75.
6. Han D, Shao X. The Vibration Analysis for a Viscoelastic Moving Fiber. *Journal of Qingdao University Engineering & Technology Edition* 120; 3: 20-26.
7. Ulsoy AG, Motec DJ. Current Research on the Vibration and Stability of Axially Moving Materials. *The Shock and Vibration Digest* 1988; 120(5): 3-13.
8. Wang Bo, Wang Zhengxing. Non-linear In-plane Vibration of Cables Considering Cable Loosening. *Journal of Wuhan University of Technology* 2009; 33(6): 1155-1159.
9. Zhou GQ, Liu XM. Viscoelastic theory. University of Science and Technology of China Press, Hefei, 1996, pp. 47.
10. Nayfeh AH, Mook DT. Nonlinear vibration analysis. Higher Education Press, Beijing, 1990, pp. 136.
11. Tagata G. Harmonically forced finite amplitude vibration of a string. *Journal of Sound and Vibration* 1977; 51(4), pp.483-492.
12. Chu YQ, Li HY. *Nonlinear vibration analysis*. Beijing Institute of Technology Press, Beijing, 1996, pp. 226.
13. Swope RD, Ames WF. Vibration of a moving threadline. *Journal of the Franklin Institute* 1963; 275(1): 36-55.

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For more information please contact:

■ **Project Coordinator:**

*Danuta Ciechańska, Ph.D. Eng.
e-mail: dciechan@ibwch.lodz.pl;
Phone : +48 42 637 67 44*

■ **Project Secretary:**

*Maria Wiśniewska-Wrona. M.Sc.
e-mail:biurofs3@ibwch.lodz.pl,
Phone: +48 42 63 80 348.*