Relevance of an Energy Dissipation as a Condition of a Stable Reeling Off of a Yarn from a Yarn Accumulator

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1. Abstract

The problems of a yarn movement and yarn tension stabilization when a yarn is reeled off from cylindrical feeders and balloons are considered. The applications of the main laws of mechanics to a part of a moving yarn with the aim to evaluate its tension lead to different results if to assume a case of reeling off without energy dissipation. The application of momentum conservation law leads to result for yarn tension value which is more than twice bigger than correspondent result following from the application of energy conservation law. Taking into account possible energy dissipation during a yarn movement resolves this contradiction. It also shows that there is necessary level of energy dissipation to insure a stable yarn movement. It explains why in a number of situations a yarn often moves by jerks and vibrates although a speed of its end, by which it is drawn, and other conditions of reeling off are maintained constant. Stabilizing influences of air resistance and additional friction are considered and evaluated.

2. Resumen (Relevancia de la energía de disipación como una condición del enrollamiento estable de hilo del almacenador de hilo)

Están considerados los problemas de estabilización de movimiento del hilo y su tensión cuando el hilo se enrolla del almacenador cilíndrico y rueda. La aplicación de las leyes principales de mecánica hacia una parte del hilo en movimiento con la finalidad de evaluar su tensión ha llevado a diferentes resultados si asumimos el caso de enrollamiento sin disipación de la energía. La aplicación de la ley de conservación del impulso lleva al resultado para el valor de tensión del hilo que es más que dos veces mayor que el resultado correspondiente que sigue de la aplicación de la ley de conservación de energía. Tomando en cuenta la posible disipación de energía durante el movimiento del hilo resuelve esta contradicción. Esto también muestra que existe el nivel necesario de disipación de energía para abastecer el movimiento estable del hilo. Esto explica por qué en numerosas situaciones el hilo frecuentemente se mueve con tirones y vibra a pesas de la velocidad de su extremo por el cual se jala y otros condiciones del enrollamiento se mantienen constantes. La influencia estabilizadora de la resistencia del aire y la fricción adicional están consideradas y evaluadas. A pesar de los detalles de consideración provistos para máquinas de tejer los enfoques propuestos son válidos para diferentes aplicaciones de la mecánica de hilos y la mecánica de cables y cuerdas.

Palabras clave: hilo, enrollamiento, tirón, vibración, tensión, almacenador de hilo, máquinas de tejer, resistencia del aire, disipación de energía.

3. Introduction

A specific feature of textile weaving machines is the necessity of fulfillment of highly complicated operations with a yarn

that has no sufficient rigidity, moves at a high velocity and does not allow for high strains [1, 2]. For example, in filling insertion on weaving machines of projectile type, a filling yarn is taken up directly from a bobbin or cylindrical feeder (thread accumulator). A projectile transports a yarn at a velocity up to 35 m/s. Experimental studies of a weft movement and tension during its transportation in weaving looms with projectiles showed that a yarn movement was jerky [3, 4] and was accompanied by big oscillations of yarn tension (Fig. 1) even during a time when a projectile transported a yarn at constant velocity and all other conditions of transportation were unchanged. For this reason a yarn tension may reach extremely big values in its maximums and the movement of a yarn has irregular nature. These circumstances bring to increase of probability of breakdowns during filling insertion process and decrease of quality of fabrics produced.

In present article the movement of a yarn and its tension in a process of a yarn reeling off are considered. The stabilizing influences of air resistance and yarn friction are evaluated.

4. Yarn motion consideration

Some general features of ballooning yarn movement such as a balloon shape, dependence of yarn tension from a distance from axis of rotation are reviewing in [1, 5, 6, 7]. Nevertheless a problem of stability of stationary ballooning yarn movement is still, contains some unsolved questions. Besides the arguments given in these works incident to movement of a weft we point out on some important circumstances when a yarn is reeling off from cylinder feeder (Fig. 2).

Such feeder or thread accumulator is a smooth cylinder with a yarn wound regularly on it. We suppose that a friction between a cylinder and a yarn is negligible. It is usually a good assumption because of a small friction coefficient value between a yarn and
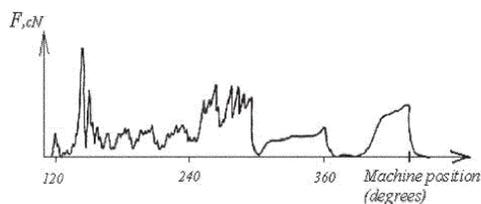

Fig. 1. Typical diagram of a weft yarn tension in a projectile weaving machine.
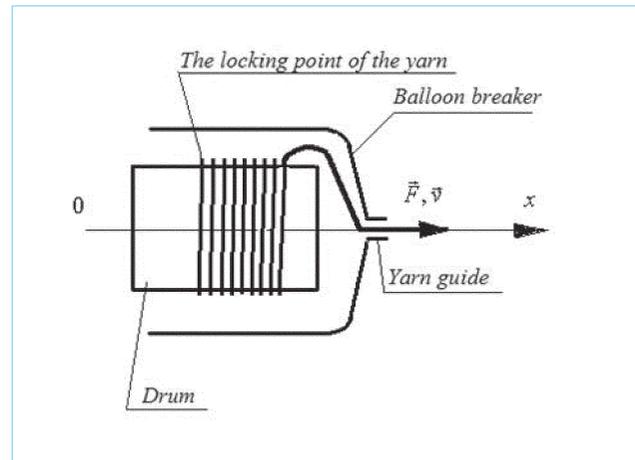

Fig. 2. Yarn reeling off from a cylinder feeder.

polished cylinder surface and absence of relative sliding motion. We also at first suppose that a yarn does not experience any friction against a balloon limiter surrounding this cylinder or against a yarn guide. We consider the problem when a yarn is pulled out from an accumulator by a loose end moving at a constant speed V along symmetry axis 0_x. Then we will take into account air resistance and yarn friction forces from a yarn guide and a balloon limiter. We proceed in this consideration from the assumption that the process of reeling off is a continuous one. It means, among other things, that a yarn length from a point of its descending point from a yarn accumulating cylinder to a point of its contact with a yarn guide has a constant or unchanged in time form and it just rotates round symmetry axis 0_x without changing its configuration.

5. Yarn tension

Let us determine force F which should be applied at a loose end of a yarn moving at a speed V as it is shown on Fig. 2 using for this determination the law of momentum conservation. This end will get ahead for a distance Vdt within a time dt. According to the law of conservation of momentum the impulse obtained by a yarn in 0_x direction equals Fdt. As a friction force between an accumulator and a yarn is negligible, efforts from a side of accumulating cylinder surface on a yarn are perpendicular to axis 0_x and so do not influence on momentum change of a yarn along axis 0_x.

From other side a change in momentum of a yarn along axis 0_x will amount to

$$\sum m_i V_{xi} - \sum m_j V_{xj} = V \sum m_n \qquad (1)$$

where

i,j indexes numbering yarn elements,

$m_i V_{xi}$ x component of momentum of a yarn element with its index i at a time moment $t + dt$,

$m_j V_{xj}$ x component of momentum of a yarn element with its index j at a time moment t,

n index numbering yarn elements what correspond a length Vdt passed by loose end of a yarn during a time dt.

Hence, if we will take into account that right side of equality (1) is equal to

$$V \sum m_n = \rho_l V^2 dt$$

we will obtain the formula

$$F = \rho_l V^2$$

where ρ_l is linear density of a yarn. Now let us note that actually a reaction force influences from a side of yarn guide on a yarn. This force is directed at approximately 135° angle to axis 0_x. This circumstance leads to an increase in force F deduced earlier. Thus, as this "neglected" force is in a direct proportion to $\rho_l V^2$ what follows from [5] and present consideration, a refined value of force at a loose end moving at a speed V will be

$$F = \rho_l V^2 (1 + k) \qquad (2)$$

where k is positive dimensionless coefficient of the order of 1.

The former result is different from the result what follows from the law of conservation of energy. Owing to an ideal contact of a yarn with a yarn guide and a balloon limiter, as well as to negligible friction between an accumulating cylinder and a yarn, we can write that total work of force F_E in the point of application on loose end which moves at a speed V should be equal yarn kinetic energy increase value

$$F_E V dt = \rho_l V^3 \, dt/2$$

Consequently, force F_E at a loose end of a yarn moving at a speed V calculated from energy consideration equals

$$F_E = \rho_l V^2 \, dt/2 \qquad (3)$$

which is more than twice less than force F, calculated according to the law of conservation of momentum.

6. Small influence of yarn elastic elongation on yarn tension during reeling off

In presented reasoning a yarn was considered as an inextensible one. It can be seen, though, that taking yarn elasticity and hence, a modification in yarn potential energy into account

will not lead to an explanation of deference in results for yarn tension received from momentum and energy consideration. Due to an insignificance of relative extension when $V \sim 30$ m/s, a share of yarn potential energy is small too.

During a time dt a segment of a yarn with length Vdt comes into motion. A work done by force F_E equals to a sum of kinetic dE and potential dP energies obtained with a yarn within time dt.

$$F_E V dt = dE + dP \qquad (4)$$

Kinetic energy of a segment brought into movement in time dt is

$$dE = \rho_l V^3 \, dt/2 \qquad (5)$$

Potential energy of this segment

$$dP \approx V dt \varepsilon \, n\rho_l V^2 /2 \qquad (6)$$

where

$Vdt\varepsilon$ is elongation of a segment brought into movement, ε is relative elongation of a yarn,

$n\rho_l V^2 /2$ is approximate mean value of tension force which changes while extending from 0 up to $n\rho_l V^2$, $n \sim 1$.

At a yarn speed $V = 30$ m/s for 200 tex yarn linear density or $\rho_l = 200 \times 10^{-6}$ kg/m we obtain $n\rho_l V^2 \sim 200 \times 10^{-6}(30)(30) = 18 \times 10^{-2}$ N.

As it follows from diagrams shown on Fig. 3 a relative elongation values of threads under such tension forces are small $\varepsilon \sim 0.02$, therefore dP value can be neglected in equality (4) because of $dP/dE \sim n\varepsilon \ll 1$.
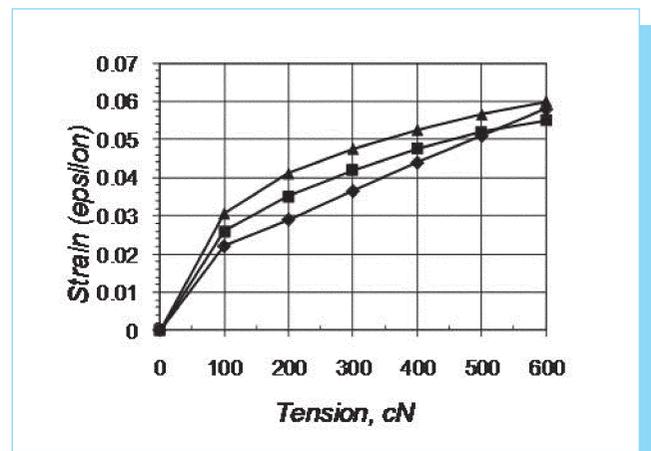

Fig. 3. Diagrams of yarn tension for different linear densities
◆ 105 tex; ■ 150 tex; ▲ 332 tex.

7. The effect of air resistance influence on the movement of a yarn during reeling off

We will need in approximate formula expressing a yarn diameter D if linear density ρ_l (kg/m) and volume density ρ (kg/m³) of yarn material (fiber) are known. A mass of an element of a yarn with its length l may be found by two equivalent ways, so it gives the equality

$$\rho_l\, l = \rho l \pi D^2/4$$

hence,

$$D = 1.13\sqrt{\frac{\rho_l}{\rho}} \tag{7}$$

Concerning volume density of a yarn (thread) it needs to mention that the fibers which are mostly in use have their volume density ρ about 1×10^3 kg/m³. So for example, for yarn linear density 100 tex (100 tex correspond linear density in SI units $\rho_l = 100\times10^{-6}$ kg/m $= 1\times10^{-4}$ kg/m) we get yarn diameter according to formula (7)

$$D = 1.13\sqrt{\frac{1\times10^{-4}}{1\times10^3}} = 3.6\times10^{-4}\,\text{m} = 0.36\,\text{mm}$$

This is quite reasonable.

An air resistance force is generally perpendicular to a yarn element, as a resistance acting along a yarn is much smaller than a one acting across a yarn [6]. A force of resistance acting across of a thread of its length dl equals to

$$dF_a = \frac{\rho_a V_a^2}{2}\, c_l D dl \tag{8}$$

where ρ_a is air volume density, V_a is speed of movement of a yarn against surrounding air, c_l is coefficient of resistance across a yarn which depends on Reynolds number $Re = D v V_a/v$, where v is coefficient of cinematic viscosity of air.

While reeling a yarn off and maintaining a speed V of its end pulled out, a speed of movement of a yarn against air will be $V_a = n_1 V$, where n_1 is a coefficient which equals approximately from 1 to 3 depending on relation of a radius of an accumulating cylinder or bobbin and a size of a balloon. For example, when loose end speed is $V \approx 30$ m/s and diameter of a yarn is $D = 3\times10^{-4}$ m then Reynolds number Re will equal approximately 900. For Reynolds number from 200 to 10 000 coefficient c_l equals 1.1 with an accuracy which is better than 10%. For Reynolds numbers bigger than 10 000 coefficient of resistance c_l equals approximately 2 [8].

Then according to (7) and (8) a power expended by a yarn segment in a balloon having length l to overcome a force of air resistance approximately equals to

$$N_r \approx 0.57 \rho_a V_a^3 l c_l \sqrt{\frac{\rho_l}{\rho}} \tag{9}$$

A difference in powers deduced from the law of modification of momentum and from the law of conservation of energy can reach

$$N_a = n_2\, \frac{\rho_l V^3}{2} \tag{10}$$

where n_2 is coefficient, which has the order of 1.

If this power representing an excess of power which needs to be absorbed for the purpose of stabilizing of the yarn movement, which is being reeled off, can be related to power spent on overcoming air resistance force, then air resistance becomes significant and it stabilizes yarn movement.

Setting equal this excess of power needed to be absorbed by air resistance and air resistance power, we obtain the equation

$$n_2\rho_l = 1.13 \rho_a n_1^3\, l c_l \sqrt{\frac{\rho_l}{\rho}} \tag{11}$$

This equation has the interpretation as follows. For any yarn linear density ρ_l there is a balloon length $l_a(\rho_l)$ that air resistance stabilizes yarn movement by absorbing excess of energy applied to a yarn of such length in a process of its reeling off. According to equation (12) at air volume density $\rho_l = 1.2$ kg/m³ and values of c_l, n_1 and n_2 as it was said above we receive this approximate dependence

$$l_a \approx 18.7\sqrt{\rho_l} \tag{12}$$

This formula gives the value l_a equal 0.19 m and 0.32 m for yarn of linear densities 1×10^{-4} kg/m and 3×10^{-4} kg/m (100 tex and 300 tex) respectively. These estimations show that it just becomes difficult to stabilize yarn movement during its reeling off using air resistance at technically usual dimensions of yarn ballooning part for yarn linear densities more than 300 tex because a balloon needs to increase in dimensions for absorbing excess of energy described above.

8. The account of sliding friction

Taking into account friction forces acting on a yarn from sides of a yarn guide surface and a balloon limiter surface is more complicated. Such consideration leads to equations

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$$Fdt - \rho_l V^2 k dt - \rho_l V^2 k_1 k_f \cos \alpha . dt = \rho_l V dt V \quad (13)$$

$$F_E V dt = \rho_l V dt V^2 / 2dQ \quad (14)$$

following after applications of the laws of modification of momentum and conservation of energy. Here $\rho_l V^2 k_1$ is a summary force of normal pressure on surfaces skirted by a yarn on a balloon limiter, $k_1 < 1$; k_f is an effective coefficient of sliding friction; $\cos \alpha$ is a mean value of cosine of an angle between friction force and axis 0_x; dQ increase in thermal energy in a yarn, balloon limiter and yarn guide owing to friction:

$$dQ = \rho_l V^2 k_1 k_f k_2 V dt V \quad (15)$$

Coefficient k_2 characterizes a speed of a yarn slippage with respect to a balloon limiter surface, $k_2 \approx 1$. Hence, the forces that follow from momentum and energy considerations are

$$F = \rho_l V^2 (1 + k + k_1 k_f \cos \alpha) \quad (16)$$

$$F_E = \rho_l V^2 (1 + 2k_1 k_2 k_f)/2 \quad (17)$$

Thus, if we would hope to get equal forces F and F_E we would have to suppose that

$$1 + k + k_1 k_f \cos \alpha = 0.5 + k_1 k_2 k_f \quad (18)$$

or

$$k_f (k_1 k_2 - k_1 \cos \alpha) = 0.5 + k \quad (19)$$

as $k \le 1$, $k_1 \le 1$, $k_2 \approx 1$, then we receive

$$k_1 k_2 - k_1 \cos \alpha \le 1, \quad 0.5 + k \approx 1 \quad (20)$$

It follows from (19) and (20) that a similar results for forces F and F_E can be obtained when effective friction coefficient k_f of a yarn on balloon limiter surface and yarn guide is near 1. Thus, when friction coefficient $k_f \approx 0.20,...,0.25$, what is usually for a case of a polished balloon limiter and typical yarn guide, an assumption on a smooth stationary movement of a yarn leads to a difference of the results given by formulas (16) and (17) what says that a stationary movement is impossible.

The only way to avoid this contradiction is to conclude that a yarn motion even in such simple conditions is jerky and vibrating though speed V of a loose end is maintained constant. Large coefficients of friction and increased energy dissipation can lead to a stable nature of reeling a yarn off.

A yarn movement can be unstable after a yarn going outside of a balloon limiter through a yarn guide, Fig. 3. To stabilize a yarn movement after a yarn guide passing it is recommended to install thin tender plates along a yarn pathway. A yarn will pass between these plates and dissipate an excess of its energy. To dissipate this excess of energy a friction force between tender plates must have the order of a quantity $F_{fr} = \rho_l V \Delta V$ where ΔV is the order of an expected velocity jerk.

9. Conclusions

In the case of a stationary reeling off of a yarn of a medium linear density from a smooth cylinder by a loose end moving at a constant speed and maintaining other permanent conditions a yarn vibrates and moves by jerks if energy dissipation factors are small.

Air resistance is able to stabilize yarn movement if a length of a yarn in its ballooning part is sufficiently long. However it leads to practically not acceptable size of a yarn balloon for linear yarn densities more than 300 tex.

To stabilize the nature of reeling off of a yarn it is advisable to increase coefficients of friction in order to dissipate excess of kinetic energy acquired when a yarn is reeling off.

Other way to stabilize a yarn movement after a yarn guide passing may consist in installation of thin plates along a yarn pathway. These plates would create a small friction force to quiet down yarn jerks.

Although the details of the consideration are provided for weaving machines the proposed approaches are valid for different applications of string and hawser mechanics.

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