CAUSE AND EFFECTS OF TENSION IN A DRAW-CONTROLLED WEB PROCESS LINE

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ABSTRACT

There is a common belief, supported by several technical papers and bulletins, that the tension in a web increases with velocity by the addition of the term mV^2 to the tension in a stationary web. This concept of a tension which increases with velocity is assumed to be a partial explanation of the increasing breakage of webs at higher velocities.

Certain effects of tension, such as the angle of release of a web which has been nipped to a roller and the depth of the catenary of a horizontal span, have been mistakenly believed to cause tension.

This paper shows that the web tension is not affected by the web velocity, if the tension is controlled by strain (draw ratio) as in a papermaking machine, nor is a catenary or other cause of a steady deviation in the path of the web the source of tension.

NOMENCLATURE

A	cross-sectional area of a stream of fluid or a web
F	resultant force
m	mass per unit length of web
s	length of path of web
T	tensile force
V	speed (magnitude of velocity)
V_1	incoming velocity
V_2	outgoing velocity
W	width of web
ρ	mass per unit volume
ρ_w	weight per unit volume
θ	angle of the velocity vector
θ_r	angle of wrap on roller

INTRODUCTION

Web mechanics has rarely been recognized as a discipline worthy of independent scientific study. The resulting lack of concentrated attention has led to serious fundamental misconceptions. One example is the erroneous concept that the term mV^2 is a component of the tension in the web. Another erroneous belief is that an increase in tension is caused by a steady deviation in the path of a web, such as the droop of a catenary between two horizontally aligned rollers, the steady billowing of a web because of air flow perpendicular to the plane of the web, or the angle required to peel a web which is adhering to a roller.

Chang (1) performed an extensive literature search on web flutter and related topics, then conducted analysis and experimentation on several aspects of out-of-plane dynamics. In contrast, this paper considers only steady-state phenomena, even though dynamic disturbances are sometimes self-induced because of turbulence generated by the traveling web; however, steady-state analysis is useful in dynamic conditions wherein the time constant of the span is much less than the time period of the oscillation. The state of zero natural frequency of a traveling threadline as analyzed by Chang may be a satisfactory operating condition, particularly if the web is directed into its desired path by felts, belts, or other means.

Holik (2) lists as sources of steady state tension in a free web span, including a horizontal span, and represents as cumulative in a bar graph:

(1) sticking force between web and carrier,
(2) vacuum force caused by the web's leaving the roller at high speed,
(3) friction (air drag from boundary layer)
(4) congestion pressure (pressure of air pumped by the web, roller, and felt),
(5) centrifugal force,
(6) force of own weight, and
(7) differential speed drawing.

In the above list, only the last item, differential draw, is normally a source of tension. The first four items represent energy losses and therefore dictate the minimum permissible tension at the downstream roller as determined by the differential draw. "Centrifugal force", the mV^2 term discussed in this paper, is neither an absorber of energy nor a source of tension. The weight of the web represents potential energy which is conserved in a horizontal span, and usually has a negligible effect on tension. The sag because of the weight of a web in a horizontal span is not a cause of tension, but is an indicator of tension.

The belief that the tension in a web has a component equal to mV^2 has led to a theory that web flutter is caused by a variation in tension, with this tension variation caused by the variation in m, the mass per unit length (3).

Some principles of web behavior are misunderstood because of extension of analogies into regions where they are not applicable. For example, if an elastic band is stretched around a rigid cylinder which is then rotated about its axis, the tension in the band is unaffected by the speed of rotation, as long as mV^2 is less than the tension preload in the band. If the cylinder is rotated at a velocity at which mV^2 is greater than the preload tension and if the band is forced to rotate with the cylinder but is otherwise unconstrained, then the tension in the band *does* equal mV^2. The preloaded band, however, corresponds to the usual case of a web in a papermaking machine, where the tension is determined by the ratio of roller velocities and is unaffected by mV^2.

Misunderstanding of web mechanics has undoubtedly led to useless changes in attempts to solve web handling problems, while the real source of the problem was overlooked. The belief that web tension inherently increases with speed may have been a deterrent to designing machines for higher speeds.

This paper examines the "mV^2 term" by analyzing the momentum of a web similarly to the analysis of a fluid as in an impulse turbine and examines other phenomena in light of the transport of strain, which is based on the conservation of mass (4).

DYNAMIC FORCE AND MOMENTUM

One source of misunderstanding of the effect of web inertia is the neglect of the fact that velocity is a vector quantity. If mV^2 expressed in units of force is much less than the total tension in the web, the tensile force dominates over the inertia force, so that consideration of web velocity as equivalent to speed, a scalar, is acceptable. However, if the magnitude of mV^2 is significant in comparison to the tension, the behavior may be understood by consideration of impulse and momentum, as in fluid dynamics with velocity a vector quantity. An understanding of these basic concepts will then lead to the conclusion that webs can be, and in fact sometimes now are, handled above the "critical velocity" at which mV^2 is equal to the tension and that the term mV^2 does not inherently increase the tension.

There are useful analogies between a web and a stream of liquid, but important and sometimes drastic differences. An open stream may be guided by a channel or vane, as in an impulse turbine, in which the forces result from the inertia of the fluid. In contrast, the direction of web motion is usually determined by the tension in the web reacting against rollers, with the inertia of the web usually negligible. A notable exception is in papermaking, where the speed is high, and at the wet end the mass is high and the strength is low. The wet paper is pressed against heated rollers by absorbent belts ("felts") as in Figure 1; therefore, transport of the paper web does not depend on tension.

In Figure 2, a steady open stream of fluid is guided by a vane. Application of Newton's second law written in terms of impulse and momentum results in the force exerted by the guide vane on the fluid:

$$F = m\,\Delta V, \tag{1}$$

where m is the mass flow of fluid per unit time. The force of the fluid on the guide vane is equal and opposite to the force of equation (1).

If a symmetrical jet of area A and uniform velocity impinges upon a large, flat plate which is perpendicular to the jet as in Figure 3, the horizontal momentum forces cancel each other and this special case of equation (1) therefore is:

$$F = \rho A V^2. \tag{2}$$

The right-hand side of equation (2) is the mV^2 term under discussion, if the jet were a web; however, the disintegration and uniform dispersal of a web is not generally desirable or possible.

In Figure 4, a web approaches a roller with velocity V_1, wraps the roller with the angle θ_r and exits at a velocity V_2. Even for a driven or braked roller, the difference in magnitudes of V_1 and V_2 is usually a small fraction of one percent; therefore, this difference is neglected in this discussion.

Newton's second law may be written Fdt = mdV. The left side of the equation is impulse and the right side is the change in momentum. In Figure 4(a), the web moves an incremental distance ds in the time dt, from A to A' at one end of the span of interest and from B to B' at the other end. Between A' and B, the mass and velocity are constant during the time dt, so that the momentum of this span is constant. The mass of either the entering or leaving element is $\rho A ds$. The momentum of the entering element is therefore $\rho A V_1 ds$ and of the leaving is $\rho A V_2 ds$. Equating the change in momentum to the impulse and solving for the force on the web after noting that ds/dt = V, the scalar speed:

$$F = \rho AV (V_2 - V_1). \tag{3}$$

Because equation (3) was derived by considering only the inertia, the result applies only to the inertia force, and other forces are superimposed. The condition in Figure 4 is usually achieved by forcing the web to conform to a roller by means of tension, but equation (3) is equally applicable if an untensioned web or a tensioned web with mV^2 greater than T is guided by a frictionless vane to force the velocity to make the transition from V_1 to V_2, as in Figure 5. As only the entering and exiting velocities appear in equation (3), the shape of the vane between the ends is unimportant in this hypothetical case. Furthermore, in the real case involving friction, equation (3) applies to the inertia force, with the downstream tension greater than the upstream tension by the magnitude of the friction force.

In Figure 4(b), it may be seen that $V_2 - V_1 = 2V\sin\theta_r/2$. In equation (3), $\rho A = m$; therefore,

$$F = 2\, mV^2 \sin (\theta_r/2). \tag{4}$$

The resultant force on a roller from equal tensile forces on the incoming and outgoing sides is equal to $2T\sin(\theta_r/2)$. Therefore, mV^2 has a direct (reducing) effect on the resultant force on the roller, but has no direct effect on the tension.

In most web handling applications, longitudinal tension is the primary force determining the path of the web, particularly if the path is considered only in an edge view of the web, neglecting lateral behavior and cross-web variations. However, as the momentum term mV^2 approaches the value of the tension, the effectiveness of tension in determining the path of the web is reduced, so that gravity and other secondary forces may determine the path of the web. A web can be handled if mV^2 is greater than the tension, but inertia then dominates over the tension. Wrapping a roller would then necessitate forcing it into conformity with the roller by means of a second web such as the felt in papermaking shown in Figure 1. A stationary guide vane on the outside of the desired curve, perhaps in conjunction with air flotation, is a second possibility for handling a web in a section where mV^2 is greater than the tension. A third possibility is a series of in-line nip stations, so that the inertia of the web helps to carry it in a straight line between the nip stations.

TRANSPORT OF STRAIN

Understanding the principle of transport of strain is necessary for analysis of tension, both steady-state and dynamic, in a web process. Neglect of the principle of transport of strain has led to confusion between cause and effect of tension, and to misunderstanding of isolation of web tensions by rollers.

Swift (5) in 1928 recognized that a flat power transmission belt (a special case of a web) has an inactive arc on the entering side over which no creep occurs and an active arc on the exiting side over which creep occurs as the belt makes the transition from the entering to the exiting value of strain. Therefore, if friction is sufficient to avoid complete slippage, the inactive arc will isolate upstream tension from downsteam tension disturbances in a velocity-controlled web transport system, but any amount of friction is powerless to prevent disturbance of downstream tension by upstream tension, as the upstream strain is transported to the downstream span. Further, a suddenly imposed but constantly maintained disturbance to the length of a span, such as the billowing of a web by air pressure normal to the web, creates only a temporary disturbance to the tension, because the transient strain is continuously transported out of the disturbed span.

The phenomenon of strain transport can therefore cancel the steady-state effect of a variable. Another example of the nullification of an apparent cause of tension by transport of strain is the effect of gravity on a horizontal span. If a web in a zero-gravity field is fastened horizontally without tension between two stationary supports, then the imposition of gravity would cause tension. However, if the two ends of the span are gripped by rollers which are, for the purpose of simplicity of illustration, driven at exactly the same surface velocities, with the further simplifying assumption that the web is perfectly elastic, the strain which is transported into the span and out of the span in the steady state is equal to the strain in the span immediately upstream as shown in Figure 6(b). The depth of the catenary is then an *indicator* of the level of tension, but the weight of the span does not *cause* the tension. The tension at the center of the catenary is equal to the horizontal component of the tension at the rollers, where the steady state tension is equal to the tension in the upstream span.

An unlikely variation in the above example in which the weight of the web would modify the outgoing strain and in turn the tension in the span is the case of tension so low that the ratio of depth to length of the catenary is greater than 0.3377, the value for minimum tension, with the incoming tension less than 0.7544 $\rho_w LtW$, the value which would cause the catenary of minimum tension. The catenary would then continually deepen, never reaching a steady state.

CONCLUSIONS

If the tension in a web is controlled by the relative speeds of rollers, as in a papermaking machine, the tension is not generally affected by the inertia of the web or by a steady-state disturbance to the path of the web.

The term mV^2 can be correctly understood if the velocity of the web is treated as a vector. The force required to change the path of a high-speed web can then be quantified by considering the change in momentum.

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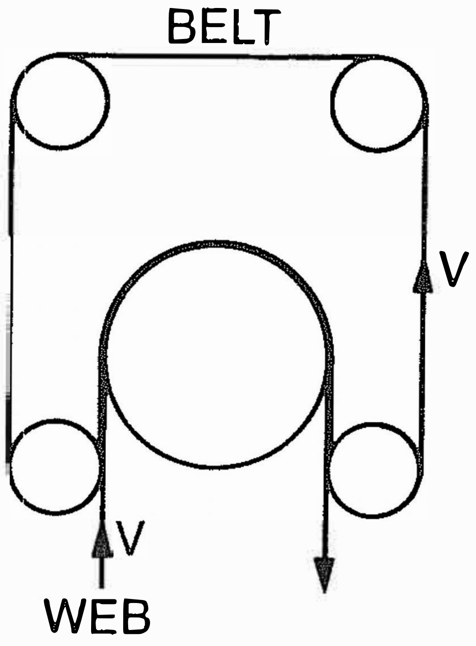

Fig. 1 Belt Pressing Wet Paper Web against Heated Roller.

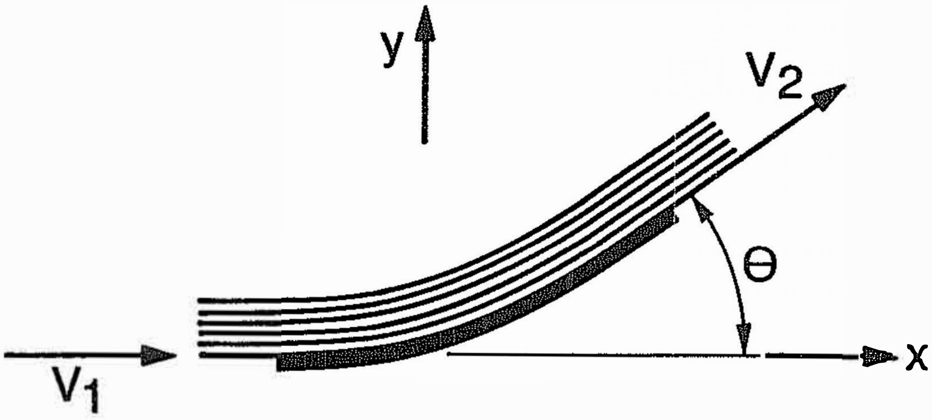

Fig. 2 Open Stream of Fluid Guided by a Vane.

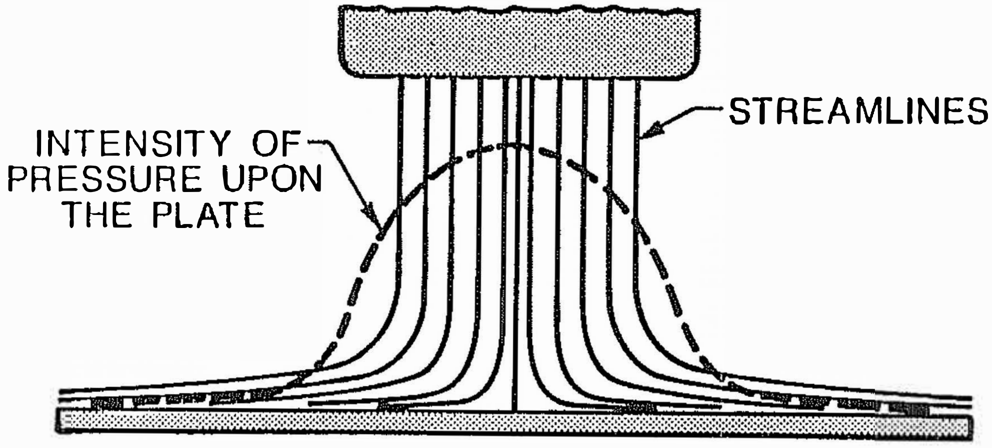

Fig. 3 A Symmetrical Stream of Fluid Impinging upon a Large, Flat Plate Perpendicular to the Stream.

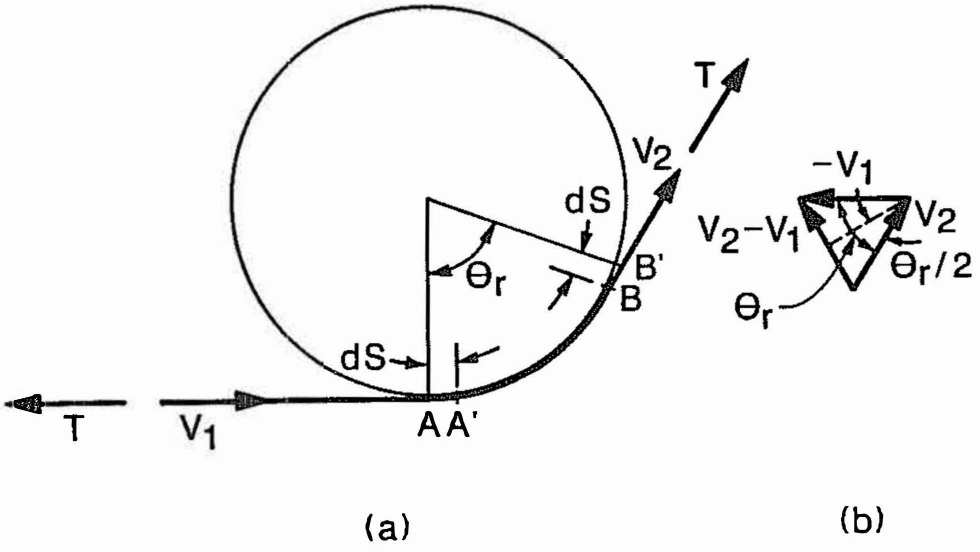

Fig. 4 Application of Principle of Momentum to a Web Wrapping a Roller.

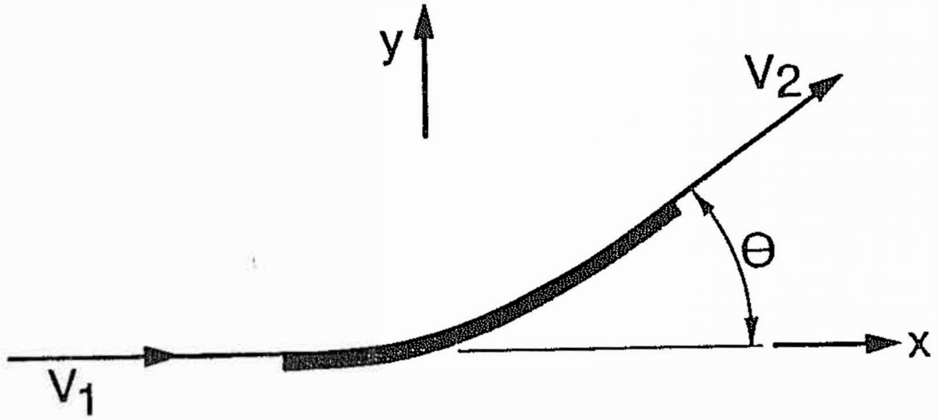

Fig. 5 A Low-Tension, High-Velocity Web Guided by a Vane.

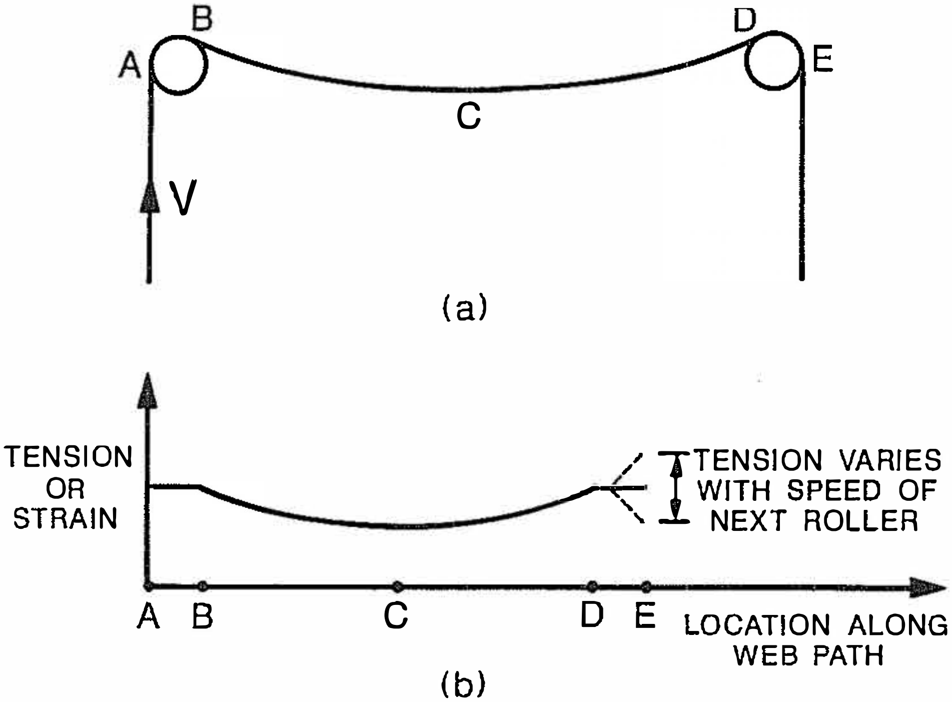

Fig. 6 Catenary of a Horizontal Web Span.

CAUSE AND EFFECTS OF TENSION IN A DRAW-CONTROLLED WEB PROCESS LINE

J.J. Shelton

Does the take-off angle θ, when a web is "peeled" off a moist roller, influence web tension, and thus, web breaks?

$$T = \frac{W}{1 - \cos\theta} + mv^2$$

Measurements of θ for a paper coater indicates tension may double due to θ; mv^2 is insignificant.
Dirk Swinehart, Mead

Well, that again is like the catenary. It is a question of cause and effect. To peel a web that is stuck to a roller as on the granite roller close to the wet end of the machine, you have to have a certain tension or it wraps the roller. The angle of peeling is an indicator of tension, not the cause of tension. You have to cause the tension with the draw ratio. If you measure tension vs. angle, then you have to decide which is the cause and which is the effect. I'm saying that the draw is the cause, and the peeling angle is the effect, as for the catenary. The depth of the catenary is the indicator of the tension, the effect of tension, not the cause of the tension. In the last paragraph under the subtitle "Transport of Strain" there is a certain case in which the catenary is very deep and it could be causing the tension, but that is a transient situation not something which can be sustained for any length of time. Free loops in metal processing lines have been used as accumulators; there the catenary could be causing the tension, but that's not the general case for web handling.

At very low tension will the speed not generate tension due to aerodynamic effect on the web surface such that it is significant vs. other tension generating causes. If yes, it contradicts your statement.
Andre Thill, Mobil Plastics Europe

Aerodynamic drag causes the tension to vary along the span of the web. This drag varies with velocity, as you know. The machine drive then must provide a higher downstream tension at the higher velocity. This paper did not say that we do not need to have a higher tension in certain sections of the machine as the speed increases, but that the tension does not increase in proportion to the momentum term mv^2. The misunderstanding which was attacked in this paper was that the tension would increase with velocity even if the web were run in a vacuum.

Aerodynamic drag increases with velocity, but bearing drag also does. You may have a drive roller, several idlers, and several free spans, and the drag is increasing with velocity. You will have a higher tension close to the drive roller and decreasing tension as you go upstream because of this drag. That is a different subject from what I was talking about. I was talking about the belief that mv^2, which is a momentum term, causes tension in the web.