The mechanics of flycasting: The flyline

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In order to propel a fishing fly through the air toward the distant quarry, a rather massive line, to which the fly is attached, is cast. As the cast line rolls out, the fly actually accelerates horizontally and seems to defy physical law. The phenomenon is modeled simplistically to determine the magnitude of this effect. In the absence of air drag, the fly can accelerate to increase its velocity by an order of magnitude. Air friction dramatically decreases the effect, but some fly acceleration is still predicted. By tapering the flyline in various ways, the fly velocity history can be significantly modified, and some tapers are predicted to perform better than others.

I. INTRODUCTION

In many recreational activities the participant is required to launch an object either for distance, accuracy, or both; examples of such objects are a baseball, javelin, rifle bullet, golf ball, ski jumper, discus, and arrow. Once the object is launched with its initial speed and direction, the only major forces that affect its path of motion are the body force due to gravity and air friction or viscous drag. In most cases, the factor that limits performance is air friction. Its minimization is the target of physical technique and equipment design. As examples, the ski jumper strives to maintain aerodynamic orientation of the skis and body, and a golf ball is dimpled to cause the air boundary layer to trip from laminar to turbulent to reduce the drag coefficient. In all cases, however, air friction diminishes the horizontal component of the object's velocity throughout its flight.

The casting of fishing lures is quite similar to the launching of the objects just described except that an additional force acts on the cast lure. The lure is tethered to the angler via the fishing line, ostensibly to allow the angler to reel in the fish but more realistically to allow retrieval of the empty lure. When the lure is cast with the aid of the fishing rod, the lure's motion is resisted by air friction and is also retarded by the force necessary to pay out the line. Hence, its horizontal velocity decreases at even a greater rate than if it were in free flight. It is easy to visualize that as the fishing lure becomes progressively lighter with a large drag coefficient, it will become virtually impossible to launch it as a projectile for any useful distance. That is precisely the problem that faces the angler who uses artificial flies as lures.

Fishing flies are designed to imitate floating insects. They are very light with a relatively large volume of feathers and fur so the surface tension acting on the large surface area can "float" the fly. Because of the large surface area, the fly's motion during a cast is easily dominated by air friction. For example, to cast a typical fishing fly horizontally 20 m from a height of 1.5 m, and no line were even attached to it, an initial velocity in excess of 140 m/s (313 mph) would be required, a prohibitive condition indeed. The solution to the flyfisher's dilemma is to cast a rather massive line to which the fly is attached and allow the fly to go along for the ride. As a result of this symbiotic relationship between line and fly, the fly (as the launched object) demonstrates a behavior during flight that is unique from all others: it accelerates horizontally. While this effect may be intuitively disconcerting, the predicting physics are quite straightforward.

The purpose of this paper is to investigate the acceleration of the cast fly and to examine the parameters that affect its magnitude. A simple model of a flycast is developed, and the equations are solved numerically to predict fly velocity history. The specific factors analyzed are these

(1) How much does fly velocity change during motion in the absence of air friction?

(2) What is the effect of air friction on velocity history?

(3) How does tapering the flyline, as is commonly done with commerically available flylines, affect fly velocity?

II. BACKGROUND

To the author's knowledge, there have been no previous studies of the mechanics of the fly and flyline during a cast. Other authors have discussed the mechanics of a fly cast, but have concentrated on the interaction between the rod and line until launch velocity is achieved.[1–3] This study, by contrast, will examine the behavior of the line from that point on. Another paper[4] examined the mechanics of the leader, which behaves similarly to the flyline, during a typical cast. However, that study assumed the velocity history for the leader rather than solving it from the work-energy equation. The cast flyline is analogous in many ways to the cracking of a bullwhip, and two studies have been reported[5,6] that analyze the velocity history for the tip of that device. None of the analyses mentioned included viscous effects of air.

III. MODEL

Flyfishers use a variety of different casts depending on the fishing conditions and their equipment. Of these many casts, probably the most common is the overhead cast. For purposes of this study, an overhead cast without any increase in line length will be modeled. To perform this cast, the angler pays out the line to the desired length by false casting where the fly is not allowed to touch the water. A backcast is then made to extend the entire line behind the caster. Analysis of the cast will begin when the line is fully extended behind the flycaster and is illustrated in Fig. 1. With the line initially straight in the backcast, the caster applies force and torque to the base of the rod to cause the rod tip and attached flyline to accelerate. As the rod straightens and then begins to flex forward, the rod tip

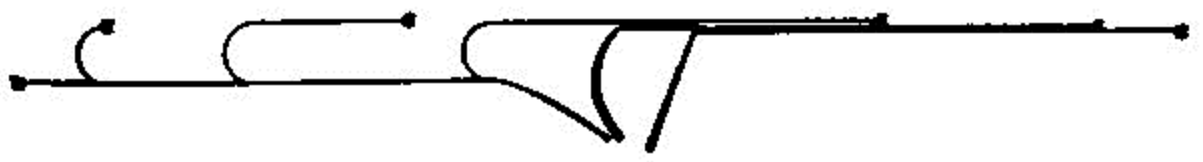

Fig. 1. Flyline motion during overhead cast.

velocity decreases and the flyline travels free of the rod motion. The horizontal flyline velocity equals the maximum horizontal component of the rod tip velocity. However, since the end of the line is attached to the rod tip, that end will have essentially zero velocity. Thus, the attached line is stationary while the remaining line is traveling, and a loop is formed at the interface between these two segments of line. Since the relative length of each portion of line will change during the cast, the loop will travel down the line like a wave until it reaches the free end of the line carrying the fly. The loop unrolls, the line straightens, and the cast is complete.

The work-energy method is employed to determine the velocity of the traveling line and the attached fly. The nomenclature and variables in the model are illustrated in Fig. 2. The cast begins with a loop of diameter D, initial line length L_0, initial mass m_0, and initial velocity V_0. In the absence of viscous drag, conservation of kinetic energy predicts the velocity of the traveling line at any time t by

$$(1/2)m(t)V(t)^2 = (1/2)m_0V_0^2 \,. \tag{1}$$

The mass of the traveling line $m(t)$ will diminish as the cast progresses since $L(t)$ decreases. The simple relationship

$$m(t) = \rho L(t) \,, \tag{2}$$

where ρ is the line mass per unit length, can be used to predict $m(t)$ if the line has uniform diameter throughout. The silk flylines used for years by flycasters are close to uniform diameter and would well fit this model. But modern polymer technology has produced flylines that have variously tapered sections along their length. These lines are used by the predominance of flycasters because of cost and performance. For these tapered lines, the volume of the traveling line must be computed and line density used. It should also be noted that the mass of the fly m_f, which is small but finite, must be added so that

$$m(t) = \rho L(t) + m_f \,. \tag{3}$$

The effects of air friction are not negligible and should be included. Since viscous drag is dissipative, the kinetic energy of the flyline during a cast will continuously decrease as work is done by the line on the surrounding air. Hence, the work-energy equation for the flyline is

$$(1/2)m(t)V(t)^2 = (1/2)m_0V_0^2 - \int_0^{S(t)} F(t)ds \,. \tag{4}$$

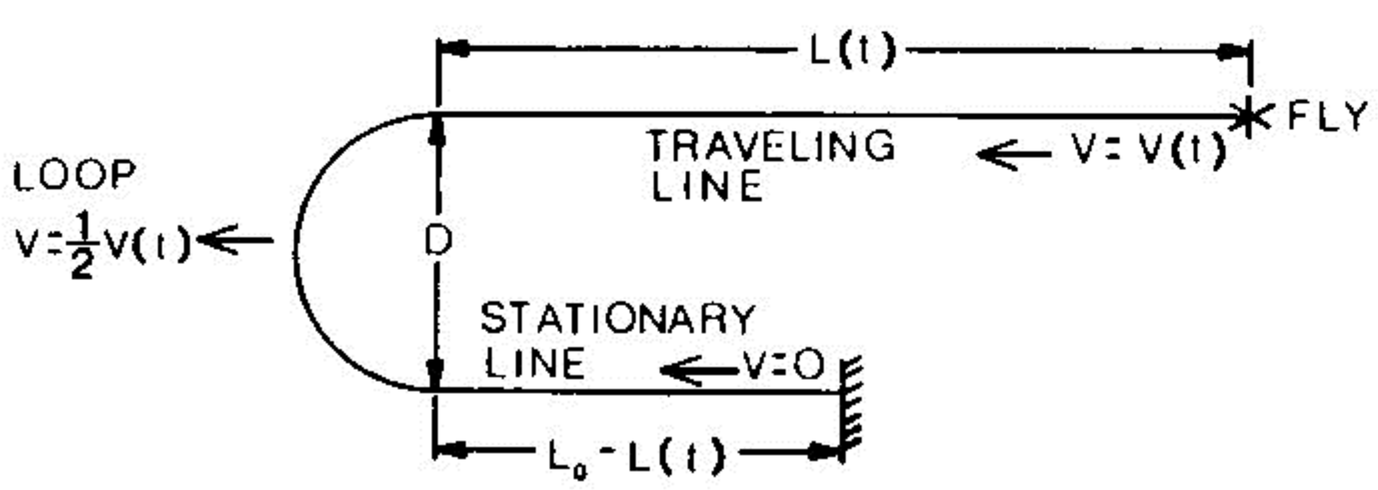

Fig. 2. Flyline model nomenclature.

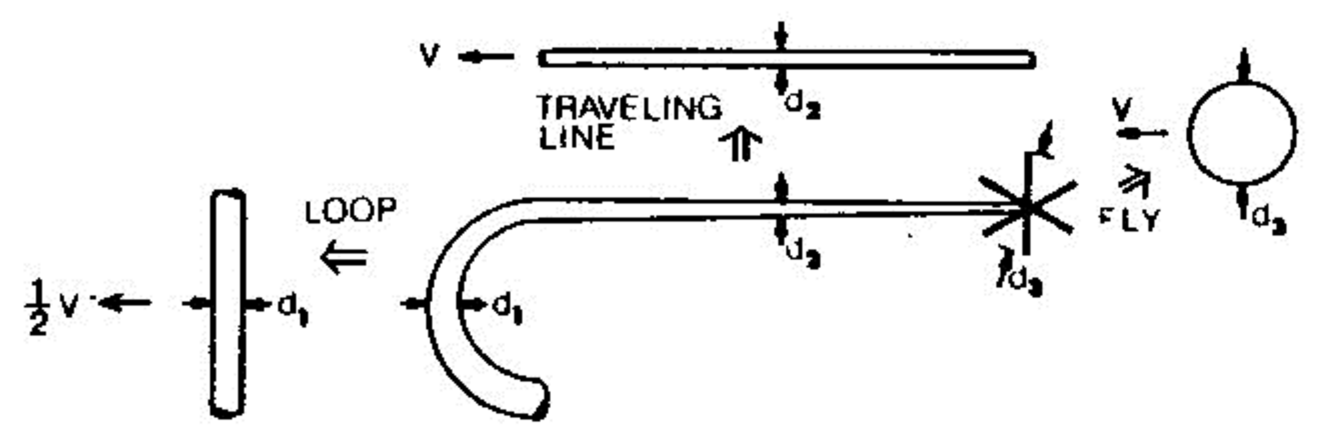

Fig. 3. Simplified flyline for drag calculations.

Also

$$ds = V(t)dt \,, \tag{5}$$

$$S(t) = \int V(t)dt \,, \tag{6}$$

$$L(t) = (1/2)S(t) \,. \tag{7}$$

The drag force $F(t)$ acting on the flyline can be written as

$$F(t) = \sum_{i=1}^{n} [(C_DA)_i(1/2)\rho_a V(t)_i^2] \,, \tag{8}$$

where it is assumed that the flyline/fly system can be separated into n distinguishable segments. Then for each segment i, C_D is the drag coefficient, A is the characteristic surface area, $V(t)$ is the instantaneous velocity (assuming zero velocity for the surrounding air), and ρ_a is air density. The major distinguishable parts of the cast flyline that contribute to the viscous drag are the loop, the traveling line, and the fly. Certain simplifying assumptions are necessary for each of these parts of these parts to allow calculation of representative drag coefficients and surface areas. The essence of each assumption is illustrated in Fig. 3, where a tapered line is modeled to indicate the effective diameters used for each segment.

The loop is modeled as a uniform cylinder in crossflow, with length equal to the loop diameter and cylinder diameter equal to the average diameter of the taper contained within the loop. The drag coefficient for a cylinder in crossflow is approximately constant and equal to 1.0 in the range of Reynolds numbers that occur in this model. The velocity of the loop is one-half that of the traveling line, so

$$V_{\text{loop}} = (1/2)V(t) \,. \tag{9}$$

The modeling of the rolling loop as a cylinder in crossflow is a major simplification but is employed for lack of a more representative model. As is demonstrated later, air drag on the loop dominates the total viscous effect, so this aspect of the model could undoubtedly benefit from refinement.

The traveling line is modeled as a long cylinder parallel to the flow, and the drag coefficient correlation recommended by White[7] for this condition is

$$C_D = 0.0015 + [0.30 + 0.015\,(L/r)^{0.4}]\text{Re}_L^{-1/3} \tag{10}$$

for $10^6 < \text{Re}_L < 10^9$.

The average diameter of the traveling line taper is used to calculate the L/r ratio as well as the line surface area.

The fly is modeled as a sphere with effective diameter of 1.5 cm, which is representative of a typically bushy, dry fly. In the range of Reynolds numbers that apply to the fly, the drag coefficient for a sphere is fairly constant and $C_D = 0.4$ is used here. Fly drag proves to be a small contribution to the overall drag, so inaccuracies in these approximations are not severe.

By combining Eqs. (3)–(10), the work energy approach yields a single nonlinear integro-differential equation for the instantaneous velocity of the fly and traveling portion of the line. The equation was solved numerically, using a mixed explicit–implicit time integration to enhance stability of the solution. The initial conditions needed to start the calculation are the initial mass and velocity. The values needed to determine the mass are the fly mass, initial traveling line length and its taper, and line density. The loop diameter is also input as an independent quantity. The velocity is calculated for each time increment, and the integrated fly displacement is found to allow examination of the spatial history of the fly velocity $V(S)$. In this way, the parametric effects on given cast length can be compared.

IV. RESULTS

The performance of a standardized cast was calculated first. All parametric variation was then compared to this standard. The characteristics of that standard cast are as follow:

(1) *Initial line length* = 20 *m*. This is also the length of the cast, or the distance from the angler to the fish. This distance would be considered fairly long for this type of cast.

(2) *Loop diameter* = 1.0 *m*. This loop diameter is typical of the average caster; good casters throw tighter loops, poorer casters throw wider loops.

(3) *Final fly velocity* = 30 *m/s*. This is the fly velocity prior to the unrolling of the leader loop and is somewhat arbitrary, since no data are available. It was chosen to represent the worst case condition for the necessary initial horizontal velocity of the fly to allow it to travel horizontally 6 m (twice the leader length) while it dropped 1 m (loop diameter). Only air drag and gravity acted on the fly during its flight, requiring a massless leader.

(4) *Flyline properties*. Line specific gravity = 0.8, implying a typical floating line. Line mass varies, but the first 9.14 m (30 ft) of each line is required to have a mass of 12.0 g (185 grains), which is the industry standard for a No. 7 line.

(5) *Flyline tapers*. Several line tapers are investigated: (A) Level (L). A commercially available line, this line has a uniform diameter throughout its length. (B) Double taper (DT). A commercially available line that is the most popular line for this type of cast. Each end of this line has a compound taper that consists of 0.61 m (2 ft) of level line, followed by 3.05 m (10 ft) of enlarging diameter line, followed by a central portion of level line. Only one end is cast, the other remaining on the reel. (C) Long taper (LT). This line exists only in the mind of this author, consisting of a uniformly increasing diameter throughout its length, starting with the same tip diameter as the commercial double taper line. This taper simulates a bullwhip. (D) Experimental taper (ET). This, too, is an invented line for analysis purposes. It also tapers to increase the diameter uniformly throughout its length like the long taper line, but the taper is less steep. The tip diameter is selected to generate very specific behavior that is demonstrated later.

Since the cast is 20 m long in each case, the fly must travel a distance of 40 m. If the effects of air friction are ignored, the velocity of fly increases continuously throughout its path as demonstrated in Fig. 4. For the level line, for example, an initial velocity of about 6 m/s is needed to produce the desired 30 m/s for cast completion. The ratio of these velocities, as an indication of line acceleration, would be greater if cast completion did not include the mass of the line in the loop traveling at the loop velocity. Since the tapered lines have a smaller diameter at the tip, hence less mass in their respective loops, they do demonstrate a greater velocity amplification than does the level line. In any case, the inviscid calculation shows that the fly does indeed accelerate during a cast.

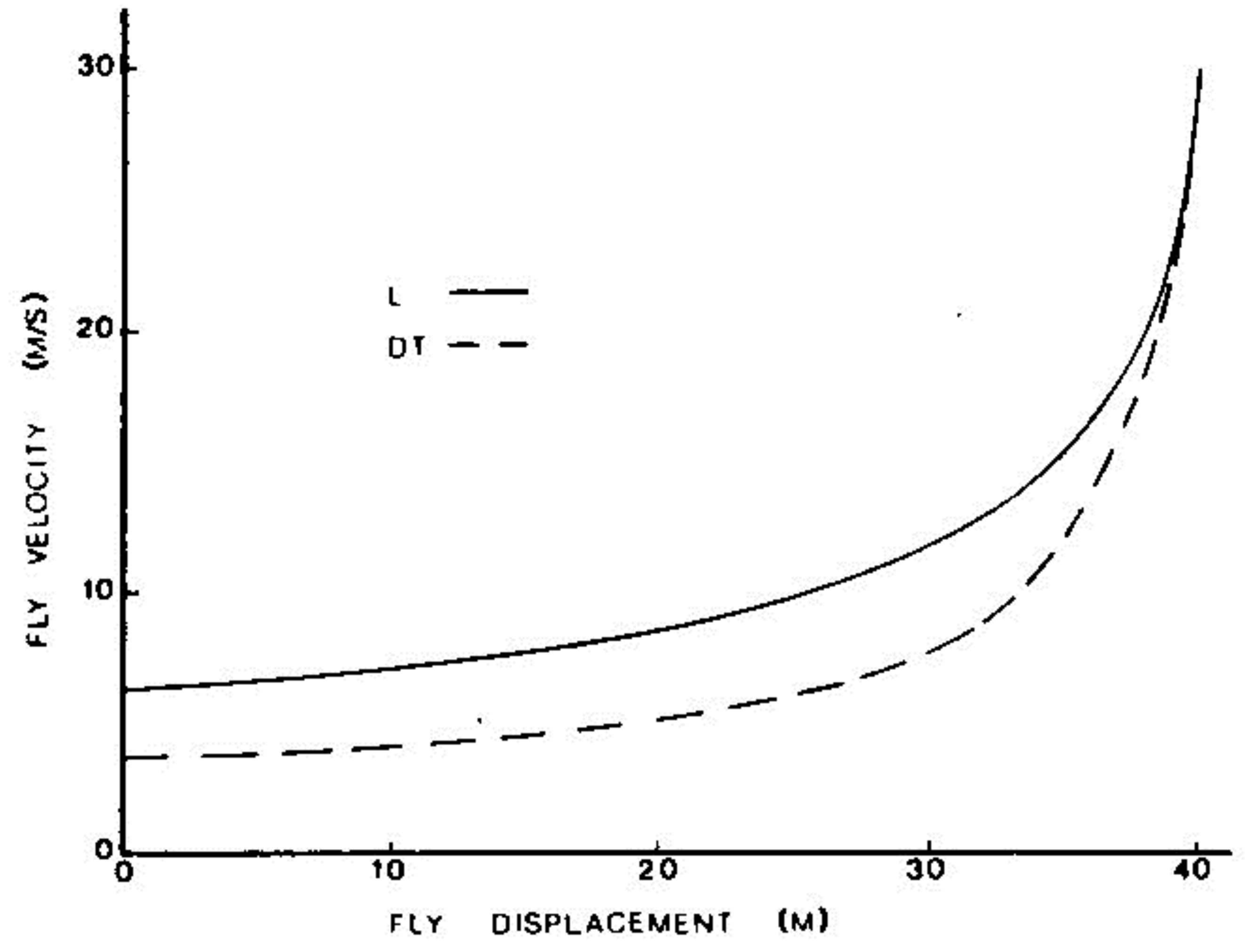

Fig. 4. Fly velocity history without air drag.

Air viscosity has very interesting effects on the fly velocity during its flight; these are illustrated in Fig. 5. Again, the final velocity for each line was fixed at 30 m/s so different initial velocities are required. In general, all lines demonstrate much more uniform velocity histories than the inviscid counterpart, with much less acceleration. The level line decelerates throughout most of its travel, and then accelerates only at the end of the cast. This behavior occurs because the viscous work for the long traveling line is greater than the corresponding velocity increase due to decreasing mass. Only as the traveling line mass becomes quite small does the relative mass change overwhelm the viscous effects.

The long taper line shows just the opposite trend from the level line in Fig. 5. This line continues to accelerate as

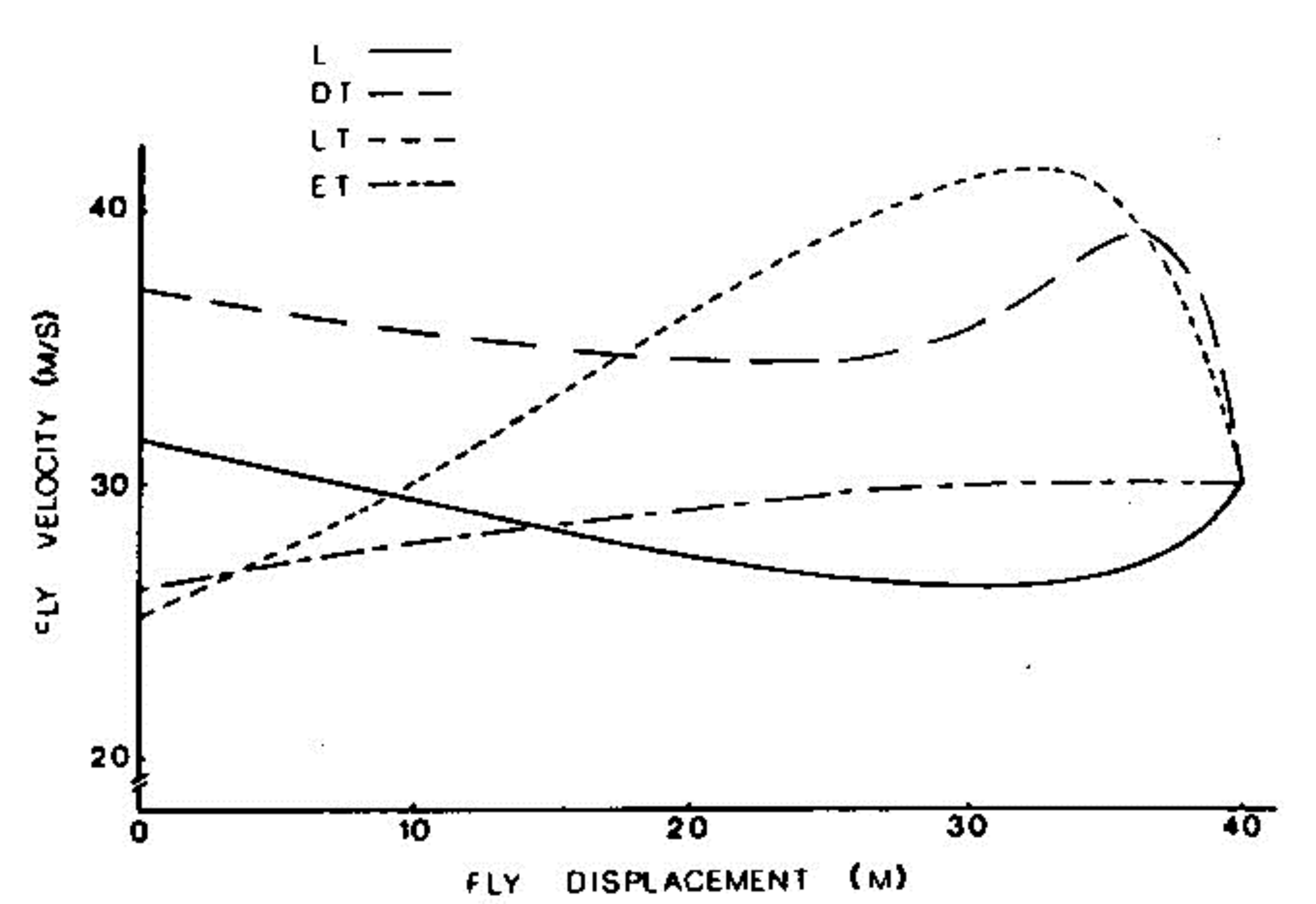

Fig. 5. Fly velocity history with air drag.

Table I. Comparison of flyline mass and energy.

Line taper	Line mass, 20 m (kg)	Initial energy (J)
Level	26.2	13.0
Double taper	30.0	20.5
Long taper	80.5	25.6
Experimental taper	48.4	16.6

the cast progresses and then rapidly decelerates at cast completion. For the long taper line, the decreasing line diameter enhances the rate of mass decrease in the traveling line. Inertial effects dominate viscous effects until the line diameter becomes quite small, at which time viscous effects take over to decelerate the fly. Since the deceleration slope is so steep, slight variations in casting technique can demonstrate a drastic impact on the delivered fly velocity.

In an effort to decouple final fly velocity from casting technique, the experimental taper was devised. Since the level line accelerates and the long taper line decelerates at cast completion, there must exist some intermediate line taper that demonstrates constant velocity at cast completion. That, in fact, is true and is demonstrated by the curve for the experimental taper in Fig. 5. Theoretically, this line should cast more consistently than those previously discussed.

Perhaps the most curious velocity history occurs with the double taper line, the most commonly used line for this type of cast. As can be seen in Fig. 5, the double taper line initially decelerates as the level central portion of the line is rolled out. As the tapered portion enters the loop, the line accelerates rather abruptly. This acceleration is quickly replaced by an even more abrupt deceleration phase until the final velocity is achieved. The velocity history demonstrates both a local maximum and a local minimum intermediate to the endpoints, a finding that was not anticipated from inviscid analysis. The distinct velocity maximization near, but not at, the end of the cast explains the characteristic "kick" that casters attribute to this line that propels a bushy fly past the end of the flyline and, in the terms of anglers, "turns the leader over." Since the taper of this line evolved from many years of "trial and error" testing, there is undoubtedly some casting benefit associated with this velocity history. Numerical quantification of this benefit is difficult at this time.

Figure 5 illustrates that each of the four lines analyzed requires a different initial velocity to produce the desired 30 m/s final velocity. The long taper line requires the smallest initial velocity, the double taper line the largest. However, the initial kinetic energy of the lines does not parallel their respective velocities because the line masses vary. Only the first 9.14 m (30 ft) of each line contains equal mass, the remaining line needed to accommodate the 20-m cast has a mass that varies with the respective tapers. Hence, as indicated in Table I, the initial energy for the level line is least and about only one-half that of the long taper line. The experimental taper line also requires relatively little initial kinetic energy. The initial line energy is of vital concern to the caster since *s/he* must feed in that energy; a long day of casting makes one very aware of efficient casting technique and equipment.

This model separates air friction effects into those acting on the loop, the traveling line, and the fly. Of those, the drag on the loop totally dominates the overall viscous loss of mechanical energy. The drag on the traveling line can be larger than that on the loop when the traveling line is long, but it decreases continuously as the cast progresses and the traveling line shortens. The loop drag remains constant, and the integrated effect over the duration of the cast emphasizes the loop drag. This is illustrated in Fig. 6, where the same cast is modeled with differing loop diameters. The initial line velocity needed to deliver 30 m/s fly velocity at cast completion increases dramatically as loop diameter increases for all line tapers. The level and experimental taper lines exhibit a somewhat weaker dependence than the other two, but for typical loop diameters that are less than 2 m, the difference is insignificant. Casting instructors constantly admonish their students to learn loop control techniques, and their words appear to be well founded. It is physically impossible to cast a zero diameter loop, both because of the inherent bending stiffness of the line and, more importantly, the inertial overshoot of the rod tip during casting. But the advantage of a loop that is as small as possible is obvious and dramatic.

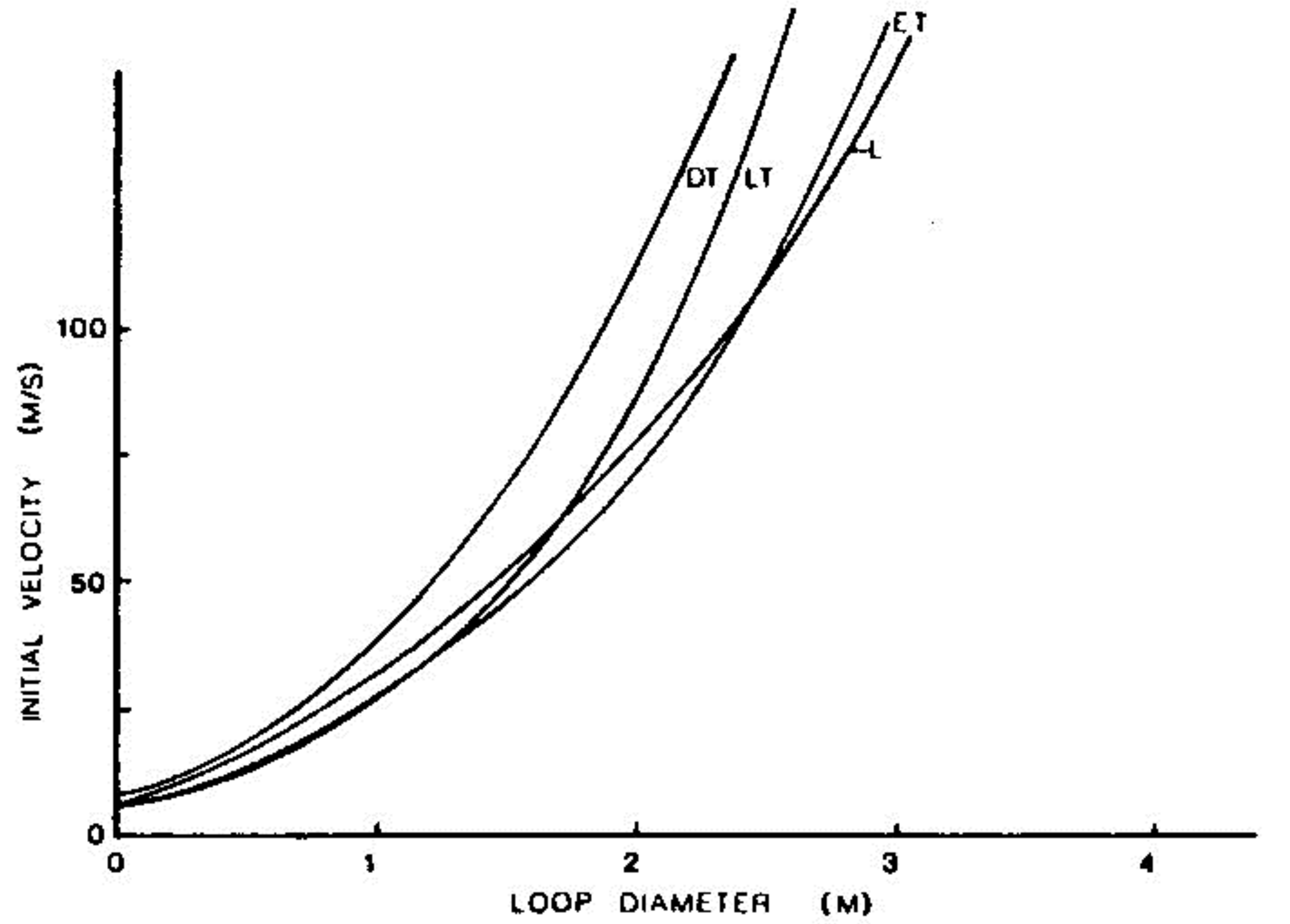

Fig. 6. Loop diameter effects on flycast.

V. CONCLUSIONS

A dynamic model of a typical flycast has been developed and used to predict the velocity history of the fly and the traveling portion of the flyline as the fly is delivered toward a specific target. The model indicates the following results:

(1) In the absence of air friction, the fly accelerates continuously throughout its flight because the mass of traveling line decrease continuously, requiring that the velocity increase to conserve kinetic energy.

(2) Air friction effects dramatically change the fly velocity history, causing differing acceleration and deceleration phases that depend on the taper of the line. It is possible to select a line taper that produces zero acceleration at the completion of the cast.

(3) The air drag on the loop that forms between the traveling and stationary line portions totally dominates the viscous effects. By minimizing the diameter of the loop the caster can significantly reduce the amount of initial energy that must be imparted to complete the cast.