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Water Sport Tow Ropes

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ABSTRACT

With the exception of tubing, towed water sports are afflicted by "wipeouts" that cause the athlete to release the handle of the tow rope. Once released, the resilience of the tow rope allows the rope and handle to spring toward the motorboat with the potential for overtaking the craft and impacting its crew. This paper examines this safety problem; specifically, it analyzes the wakeboard which subsumes water skiing, slaloming, kneeboarding and barefooting. A first order formulation is developed for describing the tow handle trajectory in terms of the system geometry, the skier's grip strength and the mechanical properties of the tow rope. A rope stiffness criterion is established that guarantees the released tow handle will fall harmlessly into the water as opposed to striking the motorboat. The handle flight time and maximum impact speed are predicted for a worst case scenario. Further, the formulation provides a guideline for refining its conservative predictions by testing rope candidates.

INTRODUCTION

In towed water sports, an athlete is propelled in the direction of a moving motorboat by gripping the handle of a specially designed lightweight rope that is attached to the watercraft. The changing relative motions of the boat and skiing athlete cause the tow rope to be alternately loaded and unloaded. When the tow rope is loaded, it stretches and stores potential energy. If the skier deliberately or accidentally releases the tow handle of the stretched rope, the handle will accelerate in the direction of the tow rope which is a two-force member. The potential energy will be converted into kinetic energy of motion.

At the moment of release, the launch angle and initial speed of the handle will cause it to assume a ballistic trajectory. If the range of the handle trajectory is greater than the skier's distance from the motorboat, the boat's occupants are in jeopardy. Injuries to towed water sport athletes have been well documented and discussed [1-7], although to a lesser extent in the area of wakeboarding [8-9]. There is no literature on the potential for injuries to boat occupants from a handle recoil mechanism. On the other hand, the Water Sports Industry Association (WSIA) has promulgated the following admonitions [10]:

- Tow ropes stretch during use. If a rope breaks or is suddenly released, it can snap back into the watercraft. Warn all riders, skiers and occupants of the danger of rope recoil.

- Rope stretches during use. Sudden release of handle can cause rope and handle to snap back and may hit the occupants or user, which could result in injury.

This paper arises from an investigation of a wakeboarding excursion that caused an aluminum handle of the towing rope to recoil onto the towing craft and strike a nineteen year old girl in the face, ultimately necessitating facial reconstruction involving a titanium forehead and cheekbone. A second girl suffered injury to her arm. The two girls, who were facing rearward, were serving as ballast along with a water bag located in the stern of an 18 ft inboard motorboat. Ballast causes the stern to ride lower in the water where it produces a larger wake for wakeboarding maneuvers. The boat was operating at 22 mph; the wakeboarder had just "gotten up" on the wakeboard when he "wiped-out", releasing the handle on the tow line. The tow rope was 65 ft in length when rigged with the handle assembly; it was fastened to a pylon in the boat that supported the rope at 8 ft above the water line. The girls watched the entire scenario, but were unable to dodge the flying handle.

A significant contingent of wakeboarders are focused on performing tricks [11]; many of these maneuvers require long air times. The use of pylons provides an upward force component on the wakeboarder which increases the air time. However, this upward tow line angle will increase the range of the trajectory resulting from a released handle. Such is not the case in water skiing which typically employs a downward tow line angle to the boat.

HANDLE TRAJECTORY – FIRST ORDER ANALYSIS

The following analysis of the tow handle impact problem adopts various idealized models of physical behavior whose deviation from reality is well understood. Our approximations nevertheless reflect the important parameters of the problem. The approach is preoccupied with the generation of conservative safety recommendations.

Hand Strength

Ultimately, the tensile load on a tow rope, P, is limited by the hand strength of the skier. Grip strength is measured as the maximum squeeze exerted on special dynamometers. The major grip strength of very strong males approaches 140 lb (63.5 kgf) [12]. Grip strength does not reflect a person's ability to maintain grasp which we distinguish as hand strength. Weight lifting experience seems to indicate that young athletes may develop hand strengths between 400 and 600 lb using both hands for short time intervals. It is difficult to imagine an athlete who cannot hang momentarily by one hand.

Resilience

The elongation Δ of a linearly elastic tow rope is given by $\Delta = PL/(AE)$ [13], or

$$P = \left(\frac{AE}{L}\right)\Delta \tag{1}$$

where P is the axial rope load, L is the rope length, A is the cross-sectional area of the rope and E is the modulus of elasticity of the rope material. If the load P is plotted against the extension Δ, one obtains a load-deflection diagram such as illustrated in Fig. 1. As indicated in Eq. 1, the slope of each straight line shown is given by (AE/L), the stiffness of the rope. Figure 1 was developed for the accident case described in the Introduction. In 2005, Gerard Schaefer obtained stiffness data for the accident rope and for a New Wakeboard Accurate Fire Jacket rope. We have replotted his data in Fig. 1 where the stiffnesses are 146.09 lb/ft for the accident rope and 1036.2 lb/ft for the New Wakeboard rope.

The input energy required to stretch a rope up to a load P is stored in the rope as potential energy and is recovered when the rope is unloaded. This recoverable energy is called resilience. It is represented by the area under the rope's load-deflection diagram up to the point (P, Δ). The resilience U of a tow rope under a load P is calculated as follows using Eq. 1:

$$U = \frac{P\Delta}{2} = \frac{P}{2}\left(\frac{PL}{AE}\right) = \frac{P^2}{2}\frac{1}{(AE/L)} \tag{2}$$

Observe that low stiffness ropes store larger amounts of recoverable energy at any load P compared with stiffer ropes.

Assume one end of an elastic tow rope is tied to a fixed point and that the handle is pulled so that the rope is stretched. When the handle is released, the rope will pull it back until it goes slack and can't pull anymore. Where did resilience or recovered energy go? The resilience is converted into the energy of motion; kinetic energy. Every particle of mass m which moves at a speed v develops a kinetic energy of $K.E. = (1/2)mv^2$. If the handle and tow rope are modeled as a simple single-degree-of-freedom mass
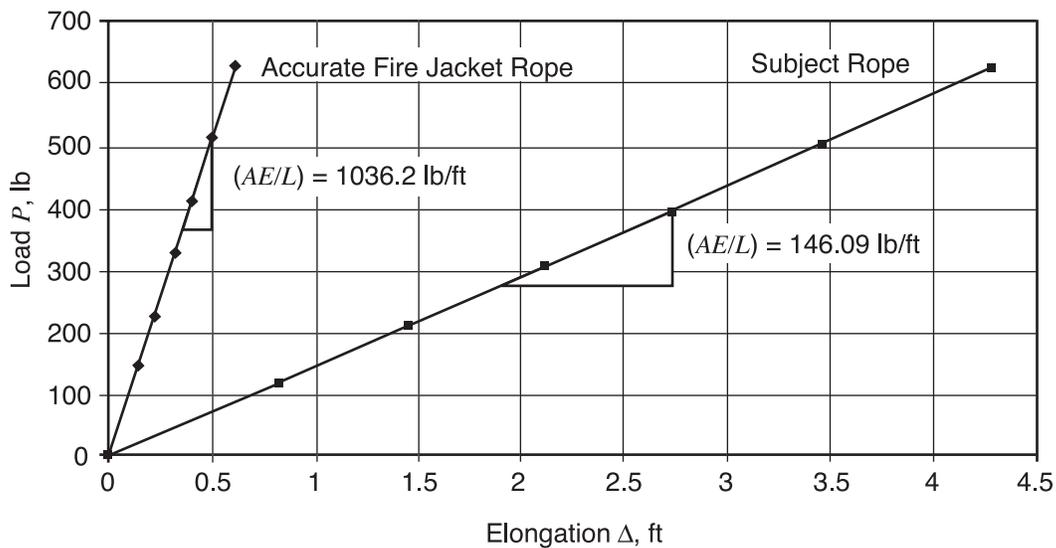

Figure 1. Load-Deflection Diagrams (Gerard Schaefer, 2005)

on a spring, the kinetic energy becomes,

$$K.E. = \frac{1}{2g}(W_h + W_r/3)v^2 \qquad (3)$$

where g is the acceleration due to gravity ($g = 32.2\ ft/sec^2$), W_h is the weight of the handle and W_r is the weight of the rope. The handle moves at a speed v and the factor 3 accounts for the kinetic energy of the rope [14]. Using the conservation of energy principle, $U = K.E.$. Thus, from Eqs. (2) and (3),

$$\frac{P^2}{2}\frac{1}{(AE/L)} = \frac{1}{2g}(W_h + W_r/3)v^2$$

or,

$$v = P\sqrt{\frac{g}{(AE/L)(W_h + W_r/3)}} \qquad \text{... launch speed} \qquad (4)$$

This speed v is the largest speed attained by the handle; it occurs when all the resilience is converted into kinetic energy.

Trajectory

The layout of the wakeboard system is illustrated in Fig. 2 where h is the height above the waterline when the wakeboarder releases the handle, H is the height above the waterline where the tow rope is attached to the elevated pylon, R is the range of the handle trajectory from release to water contact and α is the launch angle defined by the tow rope when the handle is released, i.e.,

$$\alpha = \sin^{-1}\left(\frac{H-h}{L}\right) \qquad (5)$$

The diagram shows the handle launch vector $\overline{v}$ which has the speed v given by Eq. 4 and the direction defined by α in Eq. 5.

At the time of release, the handle is subjected only to gravitational forces; it has an initial horizontal velocity of $\dot{x} = v\cos\alpha$ and an initial vertical velocity of $\dot{y} = v\sin\alpha$. If we assume the handle is moving in a vacuum, we have defined the so-called exterior ballistics problem. From the equations of motion in the y-direction (upward),

$$\ddot{y} = -g \qquad\qquad t \text{ ... time}$$

$$\dot{y} = -gt + k \qquad\qquad k \text{ ... arbitrary constant}$$

$$y = \frac{-gt^2}{2} + kt + c \qquad\qquad c \text{ ... arbitrary constant}$$

From the initial conditions we obtain,

$$t = 0,\ y = 0 \Rightarrow c = 0$$

$$t = 0,\ \dot{y} = v\sin\alpha \Rightarrow k = v\sin\alpha$$

Hence,

$$y = \frac{-gt^2}{2} + (v\sin\alpha)t \qquad (6)$$

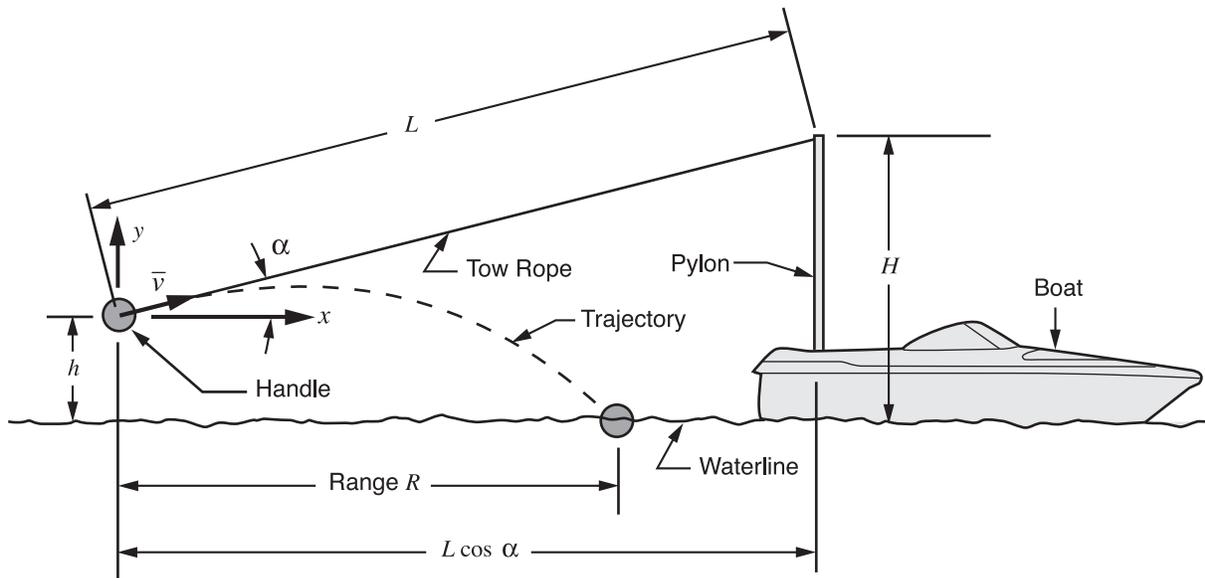$$\dot{y} = -gt + v\sin\alpha \qquad (7)$$

Figure 2. Wakeboard System Geometry: Handle Trajectory

Since the horizontal components of the handle displacement and velocity are unaffected by gravity,

$$x = (v \cos \alpha)t \tag{8}$$

$$\dot{x} = v \cos \alpha \tag{9}$$

Using Eqs. (6) to (9), we are able to define various important features characterizing the flight trajectory of the tow handle.

A. Handle Trajectory: Equations (6) and (8) provide the parametric representation of the trajectory curve, i.e.,

$$y = (v \sin \alpha - gt/2)t$$

$$x = (v \cos \alpha)t$$

These equations may be written in terms of the basic problem parameters by using Eqs. (4) and (5);

$$y = \left[P\left(\frac{H-h}{L}\right)\sqrt{\frac{g}{(AE/L)(W_h + W_r/3)}} - gt/2 \right]t$$

$$x = \left[P\sqrt{\frac{g}{(AE/L)(W_h + W_r/3)}} \sqrt{1 - \left(\frac{H-h}{L}\right)^2} \right]t$$

B. Flight Time, t^*: The elapsed time from handle release until it strikes the water, $y = -h$, is obtained from Eq. (6);

$$t^2 - \left(\frac{2v\sin\alpha}{g}\right)t - \frac{2h}{g} = 0$$

Then,

$$t^* = \left(\frac{v\sin\alpha}{g}\right) + \sqrt{\left(\frac{v\sin\alpha}{g}\right)^2 + \frac{2h}{g}}$$

or,

$$t^* = \sqrt{\frac{P^2\left(\frac{H-h}{L}\right)^2}{g(AE/L)(W_h + W_r/3)}}$$

$$+ \sqrt{\frac{P^2\left(\frac{H-h}{L}\right)^2}{g(AE/L)(W_h + W_r/3)} + \frac{2h}{g}} \tag{10}$$

C. Range, R: The handle will move horizontally at a constant speed $\dot{x} = v \cos \alpha$ until it impacts the water at $t = t^*$; thus,

$$R = (v \cos \alpha)t^* \tag{11a}$$

or,

$$R = \left(\frac{v^2 \sin 2\alpha}{2g}\right) + \sqrt{\left(\frac{v^2 \sin 2\alpha}{2g}\right)^2 + \frac{2hv^2 \cos^2 \alpha}{g}} \tag{11b}$$

or,

$$R = \frac{P^2\left(\frac{H-h}{L}\right)\sqrt{1 - \left(\frac{H-h}{L}\right)^2}}{(AE/L)(W_h + W_r/3)}$$

$$+ \sqrt{\left[\frac{P^2\left(\frac{H-h}{L}\right)\sqrt{1 - \left(\frac{H-h}{L}\right)^2}}{(AE/L)(W_h + W_r/3)}\right]^2 + \frac{2P^2h\left[1 - \left(\frac{H-h}{L}\right)^2\right]}{(AE/L)(W_h + W_r/3)}} \tag{11c}$$

Observe that every term in Eqs. 11 gets larger as the hand strength P increases, as the rope stiffness (AE/L) decreases and as the weights of the handle W_h and the rope W_r decrease.

To simplify the study of mast height H on the range R, take h=0 and recall that H is measured from the waterline. The launch angle α increases with H and the flight time of a released handle, t*, is directly proportional to H (Eq. 10). Equation (11c) becomes,

$$R = \frac{2P^2(H/L)\sqrt{1 - (H/L)^2}}{(AE/L)(W_h + W_r/3)} \quad \text{(h=0)}$$

Observe that the range is almost proportional to the mast height which makes the taller masts more dangerous. Advanced skiers extend their "air time" by increasing the lift forces with tall masts. There are no guidelines for choosing H; twelve foot is considered tall with more normal heights from eight to ten feet. Table 1 shows that the calculated and measured ranges increase with mast height.

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D. Horizontal Handle Speed, $\dot{x}$ From Eq. (9),

$$\dot{x} = v \cos \alpha$$

or,

$$\dot{x} = P\sqrt{\frac{g\left[1-\left(\dfrac{H-h}{L}\right)^2\right]}{(AE/L)(W_h + W_r/3)}} \tag{12}$$

The impact injury mechanism is primarily related to the horizontal handle speed. This velocity component is proportional to the hand strength P and inversely proportional to the square root of the rope stiffness $\sqrt{(AE/L)}$. Beware of strong wakeboarders using flexible tow lines!

E. Impact speed at waterline, v_i: At $t = t^*$ the rope handle strikes the water with an impact speed v_i; thus,

$$v_i = \sqrt{(\dot{x})^2 + \dot{y}^2(t^*)}$$

Using Eqs. (7), (9) and (10),

$$v_i = \sqrt{v^2 + 2gh}$$

or,

$$v_i = \sqrt{\frac{P^2 g}{(AE/L)(W_h + W_r/3)} + 2gh} \tag{13}$$

F. Time to Personnel Impact:

The horizontal distance between the skier and the boat space, its crew and passengers, is $L\cos\alpha$; the distance to its rope pylon. Under a constant horizontal speed $\dot{x} = v\cos\alpha$, the time from the handle release to its penetration of the boat space and potential impact with the boat crew and passengers is t_b, i.e.,

$$(v\cos\alpha)t_b = L\cos\alpha$$

$$t_b = L/v$$

or,

$$t_b = (L/P)\sqrt{\frac{(AE/L)(W_h + W_r/3)}{g}} \tag{14}$$

WORST CASE SCENARIO

A. Safety Criterion

Safety decisions are often based on "worst case" conditions so that mediation concepts may be selected that are effective. Consider, for example, the elimination of tow handle impact with the boat crew and passengers. Here, safety requires that the maximum handle range R_{max} be less than the distance from the wakeboarder to the watercraft, $L\cos\alpha$, (see Fig. 2);

$$R_{max} < L\cos\alpha \quad \ldots \text{ safety criterion} \tag{15}$$

Clearly, the range increases as the launch angle and speed increase. From Eq. 5, the launch angle is maximized by releasing the handle at the waterline, $h = 0$, and by selecting the tallest pylon height, $H = H_{max}$ and by adopting the shortest wakeboard rope, $L = L_{min}$. Also intuitively; lighter tow rope assemblies can be throw farther than heavier ones. The minimum safe rope stiffness $(AE/L)_0$ may be obtained by taking Eq. (15) as an equality and using $h = 0$ in Eq. (11c); thus

$$\frac{2P^2(H/L)\cos\alpha}{(AE/L)(W_h + W_r/3)} < L\cos\alpha$$

or,

$$(AE/L)_0 > \frac{2(P/L)^2 H}{(W_h + W_r/3)} \quad \ldots \text{ safety criterion} \tag{16}$$

where the critical stiffness $(AE/L)_0$ increases as the hand strength and pylon height increase and as the tow line length and tow assembly weight decrease. Safety is achieved whenever $(AE/L) > (AE/L)_0$. The critical flight time t_0^* and horizontal impact speed $\dot{x}_0$ associated with the critical stiffness are found by using $h = 0$ and Eq. (16) in Eqs. (10) and (12) respectively:

$$t_0^* < \sqrt{\frac{2H}{g}} \tag{17}$$

$$\dot{x}_0 < \sqrt{\frac{g(L^2 - H^2)}{2H}} \tag{18}$$

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Example: Assume the following parameters:

$P = 600\ lb$

$L = 60\ ft$

$H = 10\ ft$

$W_h = 1.5\ lb$

$W_r - 1.3\ lb$

Then,

$$(AE/L)_0 > \frac{2(P/L)^2 H}{(W_h + W_r/3)} = \frac{2(600/60)^2(10)}{1.5 + 1.3/3}$$

$$> 1034\ lb/ft$$

$$t_0^* < \sqrt{\frac{2H}{g}} = \sqrt{\frac{2(10)}{32.2}}$$

$$< 0.788\ sec$$

$$\dot{x}_0 < \sqrt{\frac{g(L^2 - H^2)}{2H}} = \sqrt{\frac{(32.2)(60^2 - 10^2)}{2(10)}}$$

$$< 75.07\ ft/sec = 51.2\ \text{mph}$$

B. Analysis Assumptions

1. The flight range of the tow handle is proportional to P^2 which makes the worst case selection of hand strength critical. The authors are unaware of data bases for hand strength which would make it possible to select the 99 percentile P for both hands. It appears that 600 lb is a reasonable extreme value.

2. The linear measure of resilience U represents an upper bound on recoverable energy. Materials that do not return along the load-deflection curve in the unloading process have converted some of the input energy into heat; this energy loss is called hysteresis and is not recoverable. For example, the hysteresis in bungee cords is 18% of the modulus of toughness. The materials used in tow ropes are usually viscoelastic; they continually stretch under constant loading and relax their resistance under a fixed elongation. They never fully return the input energy. The load-deflection curves presented in this paper reflect one of the methods used to provide an equivalent static load-deflection curve for a viscoelastic material. Beware that such methods do not properly characterize the viscoelastic behavior.

3. A single degree of freedom representation of rope behavior was assumed in computing the kinetic energy, whereas stress waves are present that gobble up energy that we assumed would be available to launch the handle.

4. Energy is dissipated in the process of releasing the handle in the pond or in the laboratory.

5. Air resistance will retard the flight of the handle and rope assembly; we assumed operation in a vacuum.

6. Wet handles and wet ropes reduce the range because of their increased weight.

7. Large rope elongations decrease the launch angle and decrease the range.

All of the assumptions used in this paper conspire to overestimate the predictions of range and impact speed.

TESTING

A very stiff and a very flexible pair of wakeboard tow ropes were tested to provide some insight into the conservative nature of our analysis and safety criterion. The two ropes were similar to the tow lines examined by Gerard Schaefer in the accident case described in the Introduction. The load-deflection diagrams of the low and high stiffness rope candidates are shown in Fig. 3. Before testing, each 60 ft rope was preloaded with 600 lb (2670 N) for two minutes to minimize viscoelastic effects. The ropes were then tested by subjecting them to axial weights; the first weight was 88.5 lb (394 N) and each additional weight was 51 lb (227 N). The time interval between loadings was 10 seconds. Immediately before and after a weight was added, the rope length was measured and the increased elongation was recorded; all subsequent stretching due to viscoelastic effects was disregarded.

Using the test set-up illustrated in Fig. 4, a series of dynamic tests were conducted with a small chalk bag attached to the handle to record the floor or wall strikes. The handle release was affected by cutting the string shown in Fig. 4 with a scalpel. All of the test parameters and results have been assembled in Table I. Observe that a pylon height of 8 ft is used in the first three rows of the test results in Table I; increasing hand strength increases the measured and predicted tow handle range for both the low and high stiffness ropes. At 500 lb (2224 N) for the low stiffness rope, the tow handle struck the laboratory wall. In each of the next three rows, the hand strength is 400 lb (1779 N); increasing
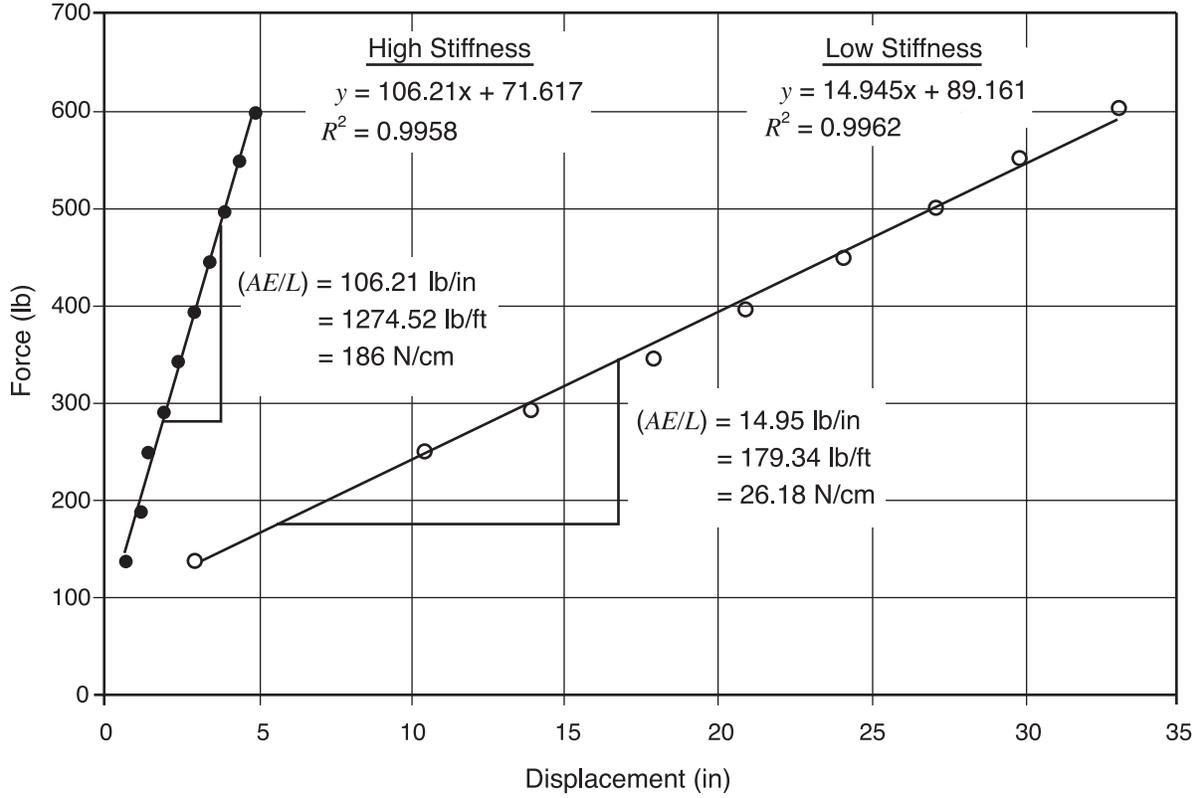
Figure 3. Load-Deflection Diagrams - Test Ropes

High Stiffness
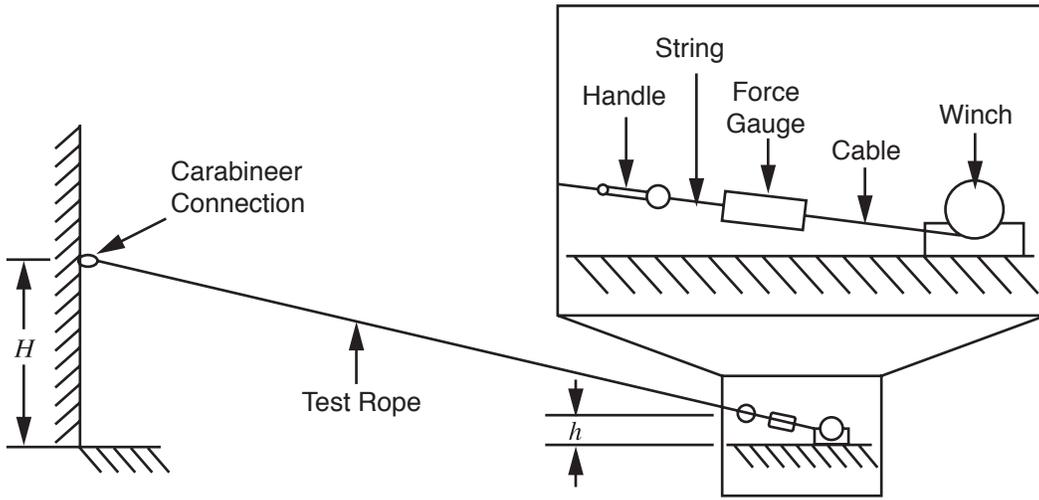$y = 106.21x + 71.617$
$R^2 = 0.9958$

$(AE/L) = 106.21$ lb/in
$= 1274.52$ lb/ft
$= 186$ N/cm

Low Stiffness
$y = 14.945x + 89.161$
$R^2 = 0.9962$

$(AE/L) = 14.95$ lb/in
$= 179.34$ lb/ft
$= 26.18$ N/cm

Figure 4. Dynamic Test Setup

Table 1. Tow Handle Range Measurements

Property	Low Stiffness	High Stiffness
L .... rope length	60'	60'
A .... rope area	0.051 in^2	0.028 in^2
W_h .. handle weight	1.78 lb	1.22 lb
W_r ... rope weight	1.29 lb	0.73 lb
(AE/L) ... stiffness	179.34 lb/ft	1274.52 lb/ft

P	H	R_c	R_m	Wall Impact	R_c	R_m	Wall Impact
300 lb	8'	47'	45'	No	11'	9'	No
400 lb	8'	79'	51'	No	19'	14'	No
500 lb	8'	127'	70'	Yes	38'	32'	No
400 lb	6'	48'	35'	No	14'	11'	No
*400 lb	8'	79'	51'	No	19'	14'	No
400 lb	10'	111'	67'	Yes	24'	17'	No
500 lb	8'	146'	--	Yes	28'	21'	No
600 lb	10'	265'	--	Yes	59'	44'	No
600 lb	10'	225'	71'	Yes	55'	41'	No

*. . . Duplicate Row; R_c = Calculated Range; R_m = Measured Range

pylon heights led to increasing range predictions and measurements for both ropes, At 10 ft (305 cm) for the low stiffness rope, the tow handle impacted the laboratory wall. The last three rows in Table I represent severe loading conditions; all three led to wall impact for the low stiffness rope; indeed, 1/4 in. Masonite fiberboard was punctured by the handle.

The high stiffness rope did not produce wall impact; note that the critical stiffness from our example is $(AE/L)_0 = 1034$ *lb/ft* which is exceeded by the stiff rope, $(AE/L) = 1274.34$ *lb/ft*   All of the predicted ranges in Table I exceed the measured ranges which demonstrates the conservative nature of our analysis. The only incorrect impact prediction in Table I occurs in the second row for the low stiffness rope; $R_c = 79$ *ft*. This range will impact the wall; however, the actual measured range was only $R_m = 51$ *ft* which did not. The analysis errs on the safe side.

OBSERVATIONS

A. The tow handle spring back hazard is reasonably foreseeable as established by the admonitions published by WSIA.

B. The severity of the impact hazard can be estimated from the horizontal handle speed. Using the parameters stated in the Example, together with the stiffness of the flexible rope, $(AE/L) = 179$ *lb/ft*, $\dot{x} = 125$ *mph*. The associated impact time from Eq. (14) is $t_i = 0.3281$ sec. This is not enough time to "dodge the bullet". Baseball batters are regularly struck by balls pitched at under 100 mph from a distance of 90 ft and they are expecting the pitch.

C. The warnings promulgated by WSIA do not describe any danger abatement methods such as impact screens or limitations on the tow rope stiffness. It is unrealistic to expect passengers to avoid a released handle in a third of a second.

D. This paper introduces the notion that a critical rope stiffness criterion exists that will eliminate the handle impact hazard. Furthermore, it provides a conservative estimate of the critical stiffness.

E. The range of the handle missile is expressed by Eq. (11c) which includes all of the system parameters in a single equation. This expression is valid for all of the towed water sports when H is taken as the elevation of the boat tow hitch. Small H values produce range levels that are short and safe.

F. Refinement of the first order analysis developed in this paper is difficult to justify because of the increased demand for technical data. In general, it is more economical to conduct full scale simulation testing programs with candidate tow ropes.

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