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Deployment Forces in Towing Systems

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Introduction

THE equilibrium shape and tension of flexible towing cables have been investigated extensively in the past.[1-4] However, the cables must withstand much higher loads. Usually the towing airplane climbs with the towed system undeployed to a certain prescribed altitude where deployment takes place. When the cable is fully extended, it experiences a sudden stretch, due to the velocity difference between the airplane and the towed vehicle. This stretch generates tension forces in the attachment point to the airplane that are much higher than in equilibrium flight. This phenomenon is similar to the snatch force generated in parachute deployment.[5] The aim of the present Note is to develop an approximate solution to the deployment forces in towing systems.

Analysis

The exact treatment of the deployment process should take account of the sinking rate of the towed vehicle and the transverse dynamics of the cable. However, this has only a minor effect on the peak deployment forces. In the present model the whole process is assumed to occur in a horizontal plane. The cable is assumed to be uniform, having linear elasticity and negligible tangential drag forces.

The deployment starts with the release of the towed vehicle from the airplane, usually in constant-speed horizontal flight. As the vehicle decelerates behind the airplane, it pulls out the cable. At the end of the deployment process the extended cable has the same velocity v_f as the decelerated vehicle. It then suddenly obtains the velocity v_0 of the towing airplane. This generates a downstream running stress wave, originating at the point attached to the airplane. The magnitude of the stress wavefront is known from the theory of elasticity to be

$$\sigma = E(v_0 - v_f)/C \tag{1}$$

where C is the wave propagation velocity and E is Young's modulus.

When treating the problem of waves in a finite solid, one has to consider also the effect of reflected waves. However, towing cables are usually very long, so that even a small amount of internal damping is enough to attenuate the stress wave, causing it to almost vanish before returning upstream. The peak stress in the cable during deployment is thus given by Eq. (1), where only the final velocity v_f is unknown.

Using the notations of Fig. 1, one obtains the rate of cable pullout and equation of motion of the towed body, respectively.

$$\frac{dx}{dt} = v_0 - v \tag{2}$$

$$T - D = m\frac{dv}{dt} \tag{3}$$

The cable equation of motion may be deduced by equating its change of momentum to the impulse exerted by the towed body

$$-T\Delta t = \mu(x+\Delta x)(v+\Delta v) - (\mu x v + \mu \Delta x v_0) \tag{4a}$$

where μ is the cable mass per unit length. This yields

$$-T = \mu\frac{d(vx)}{dt} - \mu v_0\frac{dx}{dt} \tag{4b}$$

By adding Eqs. (3) and (4b), writing the drag of the towed body explicitly, and dividing by Eq. (2), we get

$$\frac{d}{dx}[-\mu(v_0 - v)x + mv] = -\frac{\rho S C_D v^2}{2(v_0 - v)}$$

where S and C_D are the area and drag coefficient of the towed body, respectively. Performing the differentiation on the lefthand side, separating the variables and defining

$$\alpha^2 = \frac{\rho S C_D}{2\mu} \tag{5}$$

one gets

$$\int_{v_0}^{v_f}\frac{(v_0 - v)\,dv}{(v_0 - v)^2 - \alpha^2 v^2} = \frac{\mu}{m}\int_0^{\ell}\frac{dx}{1+\mu/mx}$$

The integration is straightforward, yielding an expression relating the final velocity to the parameter α and the mass ratio $\mu\ell/m$

$$\tfrac{1}{2}\left(\frac{v_f}{v_0} - 1\right) - \tfrac{1}{4}\ln\left(2\frac{v_f}{v_0} - 1\right) = \ln\left(1 + \frac{\mu\ell}{m}\right) \qquad (\alpha = 1) \tag{6a}$$

$$\frac{\alpha^2}{\alpha^2(v_f/v_0)^2 - (1 - v_f/v_0)^2}\left[\frac{(1+\alpha)v_f/v_0 - 1}{1 - (1-\alpha)v_f/v_0}\right]^{\alpha} = \left(1 + \frac{\mu\ell}{m}\right)^{2(1-\alpha^2)} \qquad (\alpha \neq 1) \tag{6b}$$

In both cases, if the mass of the cable is much greater than the mass of the towed vehicle, the final velocity tends asymptotically to

$$\frac{v_f}{v_0} = \frac{1}{1+\alpha} \tag{7}$$

which determines an upper bound to the peak deployment stress

$$\sigma_{\max} = E\frac{v_0}{C}\,\frac{\alpha}{1+\alpha} \tag{8}$$

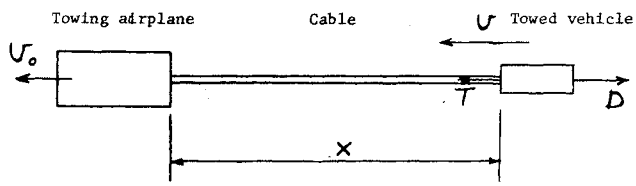

Fig. 1 Schematic diagram of towing system.

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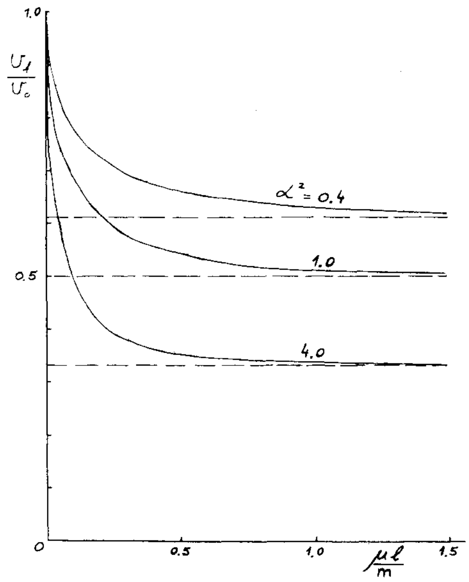

Fig. 2 Cable velocity at end of deployment.

Expressions (6a and b) are presented graphically in Fig. 2, and it may be seen that the final velocity tends quite sharply to its asymptotic value (7).

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KC-135 Boom Operator's Head-Up Display

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Refueling Operations

DURING air-to-air refueling, the receiver aircraft flies in a close trail formation slightly below the tanker. The Boom Operator (BO) lies prone, facing aft, and views the receiver through a window. The BO controls the ruddevators on the boom with a control stick in his right hand. This allows him to fly the boom from +12.5 deg (stowed position) to −45 deg (full down) and approximately 15 deg to either side. He can also extend the telescoping nozzle 0-20 ft using a control stick in his left hand. Figure 1 shows the approximate volume of coverage. If the limits in Fig. 1 are exceeded, the nozzle will automatically disconnect.

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To make contact with the receiver, the BO flies the boom to the refueling receptacle on the receiver aircraft and extends the nozzle into the receptable. During contact, he will fly the boom to follow the receiver motion. This is done to minimize the stress on the nozzle.

The BO also coaches the receiver pilot into the proper position. If the refueling limits are approached, the BO calls corrections for the receiver pilot, disconnects the nozzle, or calls for a breakaway, depending on the severity of the situation. (A breakaway is an emergency rapid separation of the two aircraft with the receiver slowing and descending and the tanker accelerating and then climbing.) Further details and descriptions are found in the air refueling technical order.[1]

Visual Problem

The primary visual problem for the BO is estimating the receiver position along the axis of the boom. He also has a great deal of difficulty in determining the actual extension position of the nozzle without looking at his gauges. His primary visual cue to determine receiver distance is the apparent size of the receiver. Since the actual size of the receiver aircraft varies from the very large C-5 or E-4 (Boeing 747) to the small fighters, this is not a reliable cue for an inexperienced BO.

The BO can estimate extension of the nozzle by viewing it directly. However, as can be seen in Fig. 2, the perspective is quite forshortened. In fact, the nozzle is not always visible, depending on boom elevation. The limits of view for the nozzle are sketched in Fig. 3. These limits were obtained by inflight observation of the extension necessary for the nozzle to be visible.

Judging the receiver position in elevation and azimuth seems to be less of a problem. There does seem to be some difficulty in determining quantitative position data and in determining proximity to the refueling limits. The rate of approach to these refueling limits seems to affect the BO's ability to judge position as well.

Night refueling is much worse, since many of the cues used by the BO are absent or greatly reduced. Clearly, the apparent size of the receiving aircraft will be quite different at night than during the day. Night operations use a light on the boom that shines down the length and illuminates the nozzle. Care must be taken to keep this light from shining in the receiver pilot's eyes. This may require a nonstandard (compared to daylight) approach to the receptacle for some airplanes.

Other Problems

Because of the receptacle design on some receiver airplanes, a reduced refueling envelope is needed. This reduces the chance of nozzle binding and an inability to disconnect. Since the limits are reduced from the normal values, the automatic disconnection feature cannot be used to prevent exceeding the refueling envelope (see Table 1). Several BO's have also commented on the need for having the receiver call sign in view.

Refueling Accidents

Using data from the Safety Center at Norton AFB, all refueling accidents for the past three years were reviewed. From these accidents, 30% were identified as significant. These accidents could have been prevented by a Boom Operator head-up display (HUD). The two criteria for including an accident in this group were failure or inability of the BO to determine proximity to the refueling envelope limits, or accident caused by the BO going "head down" to consult his instruments.

Data Requirements

The present BO instrument panel presents the following data for use during air-to-air refueling: 1) boom elevation position, 2) boom azimuth position, 3) boom nozzle ex-