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Effects of Line Ties on Parachute Deployment

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Line ties temporarily restrain a fold or folds of a parachute until deployment. The use of ties extends the time required for deployment and reduces the relative velocity between the chute and its attached forebody prior to line stretch. This paper develops a first-order theory for calculation of the effects of line ties on chute deployment time and relative velocity. Solutions are presented graphically in terms of the dimensionless parameters of the problem for a pilot-extracted-and-deployed parachute for the case of forebody velocity constant during deployment. Solutions are also given for the case of forebody acceleration constant during deployment. The problem of incorporating tie test data into parachute system design is briefly discussed.

Nomenclature

a	= acceleration, m/s^2
a_*	= aL_0/v_0^2, dimensionless
A	= $\frac{1}{2}\rho L_0(C_DS/m)_p$, dimensionless
B	= $\frac{1}{2}\rho L_0(C_DS/m)_f + (f_{avg}L_0/v_0^2)(1/m_p+1/m_f)$, dimensionless
c	= $(B/A)^{1/2}$, dimensionless
C_D	= aerodynamic drag coefficient, dimensionless
f	= line tie force, N
g	= acceleration of gravity, m/s^2
L_0	= unstretched length of parachute assembly, m
m	= mass, kg
S	= reference drag area, m^2
t	= time, s
t_*	= v_0t/L_0, dimensionless
v	= velocity, m/s
v_0	= velocity at beginning of deployment, m/s
v_*	= v/v_0, dimensionless
x	= displacement, m
x_*	= x/L_0, dimensionless
θ	= flight path angle, rad
ρ	= atmosphere mass density, kg/m^3

Subscripts

avg	= denotes average value
f	= denotes forebody
p	= denotes parachute/pack
s	= denotes separation

Introduction

LINE ties are mechanical ties which temporarily restrain a fold or folds of a parachute until deployment.[1] Sequential failure of the ties permits sequential deployment of the material retained by each tie. Ties are used to ensure an orderly, incremental deployment and occasionally to reduce the velocity of the chute relative to its attached forebody prior to significant loading of the lines.

A problem of interest in parachute system design is calculation of the relative velocity of separation between the parachute and the forebody just prior to the time at which significant tension load is placed on the chute's lines. Toni[2] analyzed this problem, but did not consider the effects of line ties; Pepper and Cronin[3] performed deployment tests to determine line tie effects for two line tie configurations; Heinrich[4] approximated line tie effects by modification of the calculated postseparation momentum with empirically determined line tie disengagement impulses; and most recently, Wolf[5] provided an analysis of the separation velocity problem without consideration of line tie effects.

This paper extends Wolf's methods for calculation of parachute/forebody separation velocity and deployment time to consideration of the effects of line ties on the deployment of a pilot-extracted-and-deployed parachute.

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Analysis

Wolf's method for calculation of the relative velocity presents results in terms of dimensionless parameters of the system. This paper generally follows Wolf's notation and assumptions.

The deployment process is shown schematically in Fig. 1. As the chute is deployed "lines first" from its pack, the pack moves aft relative to the forebody. Sequential failure of the line ties permits sequential deployment of associated sections of the parachute.

Figure 2 shows the type of force-elongation characteristic imposed on the system by the line ties. The ties may be uniform or nonuniform in strength and spacing; a nonuniform arrangement is illustrated. If it is assumed that elongation is small relative to the initial unstretched length of the parachute, an average tie force may be defined as

$$f_{avg} = \frac{1}{L_0}\int_0^{L_0} f\,dx_s \tag{1}$$

Treating the forebody and the chute pack as free bodies leads to the two differential equations

$$m_f(dv_f/dt) = m_fg(\sin\theta) - \tfrac{1}{2}\rho(C_DS)_fv_f^2 - f \tag{2}$$

and

$$m_p(dv_p/dt) = m_pg(\sin\theta) - \tfrac{1}{2}\rho(C_DS)_pv_p^2 + f \tag{3}$$

If it is assumed that $\theta_f \approx \theta_p$, then subtraction of Eq. (3) from Eq. (2), use of the variables x_s and v_s, and the transformation $dv_s/dt = v_s(dv_s/dx_s)$ may be used to obtain the expression

$$v_s(dv_s/dx_s) = -\tfrac{1}{2}\rho[(C_DS/m)_fv_f^2 - (C_DS/m)_p(v_f-v_s)^2] - f[(1/m_f)+(1/m_p)] \tag{4}$$

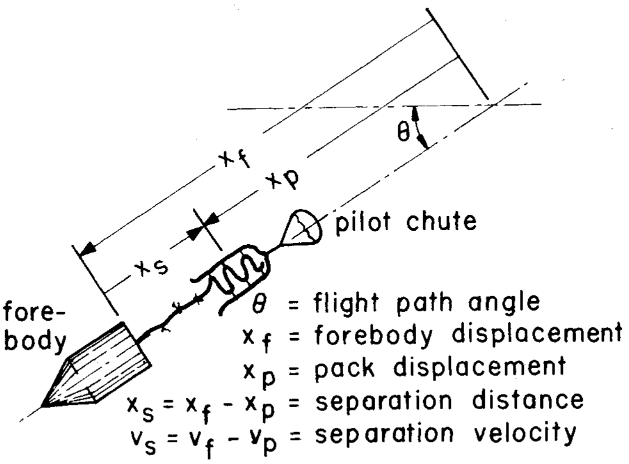

Fig. 1 System geometry.

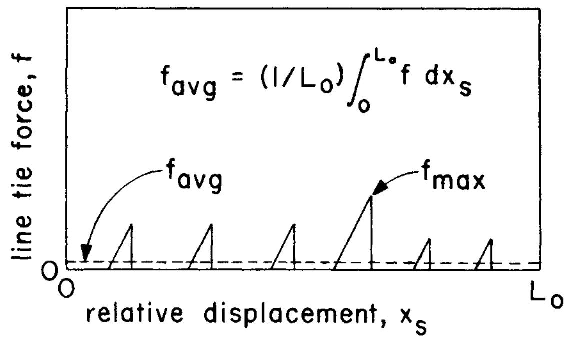

Fig. 2 Discrete line tie forces represented by an average force.

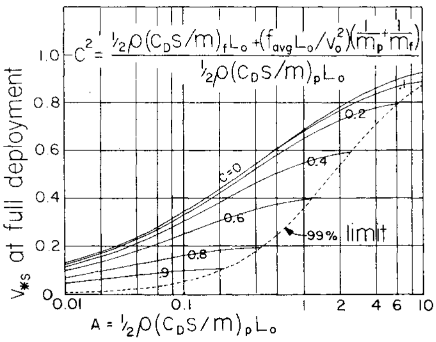

Fig. 3 Effect of line ties on relative velocity of separation (case 1: $v_f = v_0 = \text{const}$).

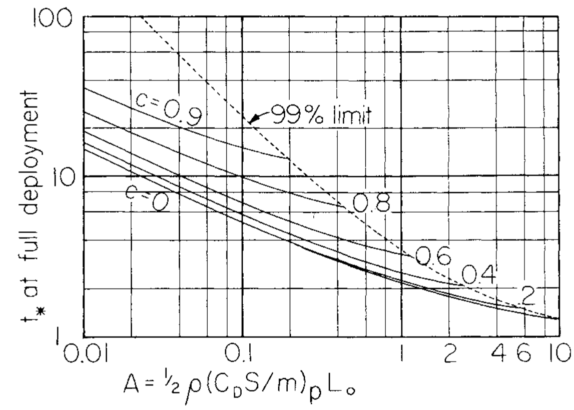

Fig. 4 Effect of line ties on deployment time (case 1: $v_f = v_0 = \text{const}$).

In preliminary design calculations, it is conventional to assume m_f and m_p constant, although part of m_p becomes associated with the forebody and m_p is also affected by accretion of an associated air mass. (One convention used has been to assign half of the suspension line mass to m_p and half to m_f.) It is also conventional to assume C_{Df} and C_{Dp} constant, although the effective value of C_{Dp} may vary appreciably as the pack moves aft through the forebody wake. If these assumptions are made, however, the additional assumption of $v_f = \text{const}$ would permit closed-form solution of Eq. (4).

Case 1: Forebody Velocity Assumed Constant

As noted by Wolf, there are many practical cases of parachute deployment in which forebody velocity does remain sensibly constant at its initial value v_0. So, following previous authors, assume that m_p, m_f, $(C_DS/m)_p$, $(C_DS/m)_f$, and v_f all remain constant and that $v_f = v_0$. With these assumptions, Eq. (4) may be put into the dimensionless forms

$$v_{*_s} \mathrm{d}v_{*_s} = [-B + A(1 - v_{*_s})^2] \mathrm{d}x_{*_s} \tag{5}$$

and

$$\mathrm{d}v_{*_s} = [-B + A(1 - v_{*S})^2] \mathrm{d}t_* \tag{6}$$

where A and B are as defined in the Nomenclature.

Equations (5) and (6) show that tie force will affect separation velocity in the same way as forebody drag force, i.e., it will decrease v_s. It is also seen that the tie force f integrated over $\mathrm{d}x_s$ from 0 to L_0 (or, equivalently, over $\mathrm{d}x_{*S}$ from 0 to 1) may be replaced by f_{avg} according to Eq. (1). In addition, Eqs. (5) and (6) show that separation acceleration becomes zero when

$$v_{*_s} = 1 - (B/A)^{1/2} \tag{7}$$

Deployment will stop if the condition in Eq. (7) is reached before attainment of $x_s = L_0$ or $x_{*_s} = 1$.

Equations (5) and (6) may be integrated from the initial conditions, taken here as $(x_{*_s}, v_{*_s}, t_*) = (0,0,0)$, to any valid set of (x_{*_s}, v_{*_s}, t_*). A "valid set" of end conditions is one which does not violate the constraint imposed by Eq. (7). Solutions to Eqs. (5) and (6) are given as follows:

$$\exp(2Acx_{*_s}) = \left[\frac{v_{*_s} - 1 + c}{1 - c}\right]^{(c-1)} \left[\frac{v_{*_s} - 1 - c}{1 + c}\right]^{(c+1)} \tag{8}$$

$$v_{*_s}/(1-c) = (e^{2Act_*} - 1) \Big/ \left[e^{2Act_*} - \frac{1-c}{1+c}\right] \tag{9}$$

$$x_{*_s} = (1+c)t_* - (1/A)\log_e\left[\frac{(1+c)e^{2Act_*} - 1 + c}{2c}\right] \tag{10}$$

where $c = (B/A)^{1/2}$.

Results from Eqs. (8-10) are shown graphically in Figs. 3 and 4. Figure 3 shows dimensionless separation velocity v_{*_s} when deployment is complete (i.e., when $x_{*_s} = 1$) vs the parameters A and c. As noted previously, the system is subject to the constraint that deployment be completed before v_{*_s} is at the critical value given by Eq. (7), else the deployment theoretically requires infinite distance and time for completion. A practical limit was therefore provided by conducting calculations only up to separation velocities of 99% of the critical value of Eq. (7). The 99% limit is shown by the dashed line in Fig. 3.

The valve of $c = 0$ corresponds to the case of no line ties and negligible forebody drag force..

Figure 4 shows dimensionless deployment time t_* vs A and c for $x_{*_s} = 1$. The 99% limit noted previously is also indicated in Fig. 4.

Case 2: Forebody Acceleration Assumed Constant

Another practical case encountered in parachute deployment is that of sensibly constant forebody acceleration. This may occur, for example, when a relatively heavy forebody is released from a first-stage chute and is accelerated primarily by gravitational force during deployment of the second-stage chute. For such a case, Eqs. (3) and (4) become, respectively,

$$m_f(\mathrm{d}v_f/\mathrm{d}t) = m_f a_f \tag{11}$$

and

$$m_p(\mathrm{d}v_p/\mathrm{d}t) = m_p g(\sin\theta) - ½\rho(C_D S)_p v_p^2 + f \tag{12}$$

With the same dimensionless variables as before and with $a_* = a_f L_0 / v_0^2$, Eq. (11) has the solutions

$$v_{*_f} = 1 + a_* t_* \tag{13}$$

$$x_{*_f} = t_* + ½ a_* t_*^2 \tag{14}$$

and

$$v_*^2 = 1 + 2a_* x_{*_f} \tag{15}$$

And with the same assumptions used previously, except that of $v_f = v_0 = \mathrm{const}$, Eq. (12) may be solved to get

$$\frac{1+c+(1-c)e^{-2Act_*}}{1+c-(1-c)e^{-2Act_*}} \tag{16}$$

$$Ax_{*_p} = Act_* + \log_e\left[\frac{(1+c)-(1-c)e^{-2Act_*}}{2c}\right] \tag{17}$$

and

$$v_{*_p}^2 = c^2 + (1-c^2)e^{-2Ax_{*_p}} \tag{18}$$

There are too many dimensionless parameters involved in Eqs. (13-18) for facile graphical display of v_{*_s} and x_{*_s}, the separation variables of interest. However, the appearance of A, c, and t_* as a lumped product in Eqs. (16) and (17) does permit relatively quick calculation of values of v_{*_p} and Ax_{*_p} vs the two parameters c and (Act_*).

To calculate results for a system with known parameter values and with an assumed constant forebody acceleration, one may use Eqs. (14) and (17) to determine values of x_{*_f} and x_{*_p}, respectively, vs t_*. A solution has been obtained (in the mathematical sense) when $x_{*_f} - x_{*_p} = 1$ (i.e., when $x_s = L_0$) at a common value of t_*. Parametric solutions of Eqs. (13-18) may, of course, easily be generated on a digital computer. For that matter, the digital computer may be used to obtain solutions of Eqs. (2) and (3) in the displacement or time domains without many of the simplifying assumptions necessary to obtain the closed-form solutions presented here.

The Design Problem

The usual design problem is to devise a line tie arrangement which will give a specified v_s at the end of deployment for a system with known parameters and with v_0 set by other system constraints (e.g., v_0 may be the terminal velocity of the forebody). Thus, one must specify detailed design of the ties and then calculate their effects to ensure that the system does not exceed the specified v_s.

In preliminary design, the effects of the line ties may be calculated approximately and compared with forebody drag effects by recourse to Figs. 3 and 4. In those figures, one may either exclude or include the effects of the forebody ballistic factor $(C_D S/m)_f$. Its effects may be excluded by setting $(C_D S/m)_f = 0$. If this is done, the calculated separation velocity will be too large because forebody drag has been neglected. However, if $(C_D S/m)_f$ is included, the calculated separation velocity will be too small because it has then been assumed that the initial dynamic pressure $½\rho v_0^2$ acts on the forebody during the entire deployment sequence. Upper and lower limits for the separation velocity as well as an indication of the relative effects of forebody drag and line tie forces may thus be obtained.

The next step is to apply the f_{avg} value obtained from calculations to the actual design. Generally, the use of many relatively light ties is preferred to the use of a few heavy ties. Tie locations are usually dictated by the parachute and pack configurations.

The force vs elongation characteristic of a proposed line tie arrangement may be evaluated by bench-testing the pack with a tensiometer, which is used to record force vs time as the chute is deployed from the pack by a suitable constant-speed drive. If more elaborate tie data are desired or required, sample tie specimens may be tested in a tensile testing machine to obtain force vs elongation for each type of tie. An overall force-elongation plot for the deployment may then be developed from the specimen test data. Pack bench-testing has the advantage of also indicating the friction forces. Individual tie testing has the advantage of determining beforehand the force-elongation nature of each type of tie so that the number and types of ties required can be assigned during design of the chute/pack interface.

Conclusion

The material presented here should be adequate for preliminary design calculations to determine the effects of line ties on parachute deployment separation velocity and time. The designer should, however, note the many simplifying assumptions used in the derivations. The effects of such assumptions should be carefully considered for each particular case, even though the same assumptions appear in most conventionally used parachute separation velocity and snatch force calculations.

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