COBEM 99
XV Congresso Brasileiro de Engenharia Mecânica
15th Brazilian Congress of Mechanical Engineering
22 - 26 de Novembro de 1999 / November 22 - 26, 1999 Águas de Lindóia, São Paulo,

SIMULATION OF PARACHUTE DYNAMICS

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Abstract. *Small returnable orbital payloads or spacecrafts need safe, efficient and affordable recovery systems. Systems based on parachutes are the most reliable choice due to its proven reliability and low cost. The present work deals with the modeling and simulation features of a high performance ground recovery system based on parachutes. The proposed dynamic models comprise an elastic parachute with apparent air influence. The paper shows and discusses the results of the system motion simulation and tests.*

Keywords**:** *Parachute deployment, Apparent air, System dynamics*

1. INTRODUCTION

Parachutes are used as aerodynamic decelerator systems for a wide spectrum of applications, as for instance: load recovery after drop test, rocket payload recovery, space-aircraft landing deceleration, vehicle stabilization etc.(Koldaev & Moraes, 1996, Moraes, 1997). The development of such a system includes the consideration of filling time, inflation dynamics, ballistic and wake flow characteristics.

Therefore a lot of work (Rysev, 1997, Mosseev, 1997, Strickland, 1996) has to be initially done concerning the dynamic modeling concept of the recovery system. A good concept leads to maximization of performance and consequently to weight minimization of the complete system, which is of great importance for space systems (Deweese, Schultz & Nutt, 1978).

Great effort should be done in elaboration and execution of several modeling methods and programs of simulation. The present paper shows and discusses the mean aspects of the preliminary simulation of the parachute-capsule system dynamics and its comparison with testing.

2. MODELING OF PARACHUTE DEPLOYMENT AND SYSTEM MOTION

2.1 Parachute deployment

Parachute deployment means the sequence of events that starts with the opening of a parachute compartment or parachute pack attached to the body to be recovered. Deployment continues with extraction of the parachute until the canopy and suspension lines are stretched behind the body and the parachute canopy is ready to start the inflation process. The parachute drag area, $(C_DS)_p$, increases from close to zero at line stretch to $(C_DS)_o$ with full open canopy.

The following simplified formulas are presented in the relationship between the resultant parachute drag forces and the recovery system parameters, (Knacke, 1992, Macha, 1993):

Ratio $$S^* = (C_DS)_p \;/\; (C_DS)_o \qquad (1)$$

versus dimensionless time ratio T can be determined as

$$S^* = A\,T^B + (1\text{-}A)\,T^2 \qquad (0 \le T \le 1) \qquad (2)$$

$$T = t \,/\, t_f\,, \qquad (3)$$

where S^* - parachute area ratio, dimensionless
t_f - parachute filling time, s
T - filling time ratio, dimensionless
A, B - constants of parachute filling style, dimensionless .

2.2 System motion

For a symmetrical neutral parachute-capsule system, the trajectory equations of motion in space can be written in the form, "Fig.1":

$$(m_c + m_p)\, dV / dt = -\,F_p - F_c - (W_c + W_p)\sin\theta - d(V\,m_a)\,/\,dt \qquad (4)$$

$$m_c\,V^2 / R = -\,W_c \cos\theta \qquad (5)$$

$$dH = V\sin\theta\;dt \qquad (6)$$

where V - trajectory velocity, m/s
m_a - mass of apparent air (added mass), kg
m_c - mass of parachute, kg
m_p - mass of the vehicle (capsule), kg
F_p - parachute force acting parallel to the flight trajectory, N
F_c - drag of the vehicle capsule, N
W_c - weight of capsule, N
W_c - weight of parachute, N
R - radius of trajectory, m
θ - trajectory angle from the horizontal plane, degrees (rad)
H - altitude of motion, m.

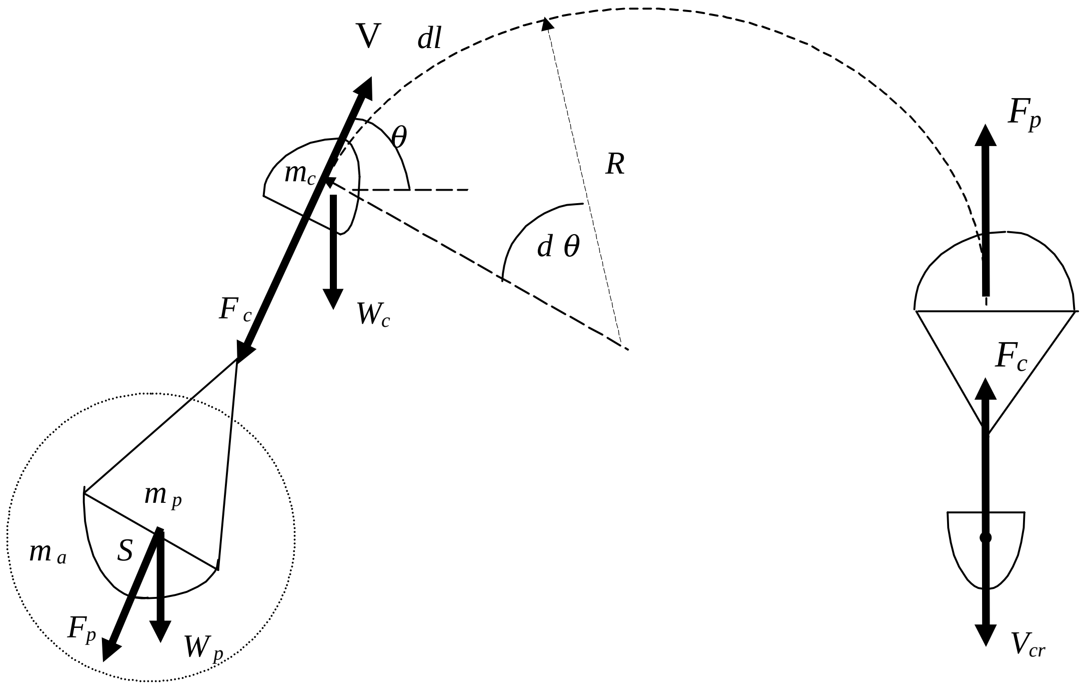


Figure 1 - Parachute - capsule system motion in space

Radius of trajectory R for every moment can be determined after the equation :

$$dl = R\ d\theta = V\,dt \tag{7}$$

or $$R = V\,dt\,/\,d\theta \tag{8}$$

The drag of the capsule, D_c , depends on the drag area of the vehicle and on the instantaneous dynamic pressure, which changes during the opening process of the parachute.

The trajectory angle, θ, changes from the deployment angle to vertical most rapidly during and after parachute inflation. When parachute capsule system is lifting, the angle $\theta > 0$.

The apparent or added mass, m_a, is calculated by multiplying volume by density and by a form factor that depends on the parachute particular type.

The recommendation (Knacke,1992) for parachute apparent air mass is:

$$m_a = (4.75 \text{ to } 5.43)\ \rho\, D_p^{\,3} / 8 \tag{9}$$

$$D_p = D_o\, D_p^* \tag{10}$$

then $$D_p = 2\, D_p^* \sqrt{S/\pi} \tag{11}$$

$$m_a = (0.854 \text{ to } 0.977)\ \rho\, S^{3/2}\, D_p^{*3} \tag{12}$$

$$K = m_a / (\rho\, (C_D S)_o^{\,3/2}) = (0.854 \text{ to } 0.977)\ D_p^{*3} / C_D^{\,3/2} \tag{13}$$

$$m_a / m_c = K\ S^{*3/2}\, \rho\, (C_D S)_o^{\,3/2} / m_c \tag{14}$$

where D_o - nominal diameter of canopy, m

D_p - diameter of filled canopy projection, m

D_p* - ratio of projected diameter to nominal diameter of canopy, dimensionless

S - area of parachute canopy, m^2

K - parameter of apparent parachute air mass, dimensionless

C_D - parachute drag coefficient, dimensionless.

For real parachutes with $D_p* = 0.62\text{-}0.94$ and $C_D = 0.45\text{-}0.95$ we have $K = 0.6\text{-}0.8$.

If $$R_m = \rho (C_D S)_o^{3/2} / m_c \qquad (15)$$

$$F_p = (C_D S)_o \rho V^2 / 2 \qquad (16)$$

$$F_c = C_c S_c \rho V^2 / 2 \qquad (17)$$

$$W_c = m_c g \qquad (18)$$

$$W_p = m_p g \qquad (19)$$

$$C* = 1 + (C_c S_c / (C_D S)_o) \qquad (20)$$

$$W_c + W_p = F_c + F_p \qquad (21)$$

then $$(m_c + m_p) g = ((C_D S)_o + C_c S_c) \rho V_{cr}^2 / 2 \qquad (22)$$

and $$V_{cr} = (2g (m_c + m_p) / (\rho (C_D S)_o C*))^{1/2} \qquad (23)$$

If $$m_p* = m_p / m_c \qquad (24)$$

$$m_a / (m_c + m_p) = K R_m S*^{3/2} / (1 + m_p*) \qquad (25)$$

$$V* = V / V_{cr} \qquad (26)$$

$$t* = t g / V_{cr} \qquad (27)$$

we can write from Eq.(4), (5), (6), (8) and (15) following non-dimensional equations:

$$dV* / dt* = - (\sin\theta + S* V*^2) / (1 + K R_m S*^{3/2} / (1 + m_p*)) \qquad (28)$$

$$d\theta / dt* = - \cos\theta / V* \qquad (29)$$

$$dH* / dt* = V* \sin\theta \qquad (30)$$

where V_{cr} - velocity of system settle rate of descent, m/s

R_m - mass ratio of apparent mass to capsule mass, dimensionless

$S*$ - parachute area ratio, Eq. (1), dimensionless.

Time ratio T versus dimensionless time $t*$ can be determined by Eq.(1) and Eq.(3) as:

$$t_f = C\sqrt{S} / V_o \qquad (31)$$

$$T = t / t_f = t^* V_{cr} / (g\, t_f) = t^* V_{cr} V_o / (g\, C \sqrt{S}\,) \tag{32}$$

where C - constant of parachute filling, dimensionless

S - area of parachute canopy, m^2

V_o - velocity of system at the beginning of filling, m/s.

2.3 Description of numerical method

Due to sequence of events which the mathematical modeling intends to capture, an explicit method of solution of the equations was chosen. Multistep-method type of Runge-Kutta was used for the temporary discretization. Among the basic characteristics of these method we should mention:

- they are self-initialized, that is, starting from the initial condition it is possible to calculate the other points solution. It should be noticed that, for the simulation accomplished in the present work, the transition of an event for another was obtained by simple establishment of the initial conditions and involved equations;
- they do not request the calculation of having derived, with facilitated the opening force simulation;
- the method allows to control easily the size of the step in the time level and, obviously, care should be taken in obeying of the limits of stability of the method;
- finally it uses 'p' evaluations of the function to each step, where 'p' defines the order of the method. In this context, the inclusion of intermediary stage allows the control of the characteristics of stability, precision and computational cost.

Runge-Kutta schemes are computationally expensive since the equations system (28)-(30) are nonlinear equations which must be solved interactively for each time step. Temporary integration of the system of equations:

$$\begin{aligned}
&y^{(1)'} = f^{(1)}(x, y^{(1)}, \ldots, y^{(r)}) \\
&y^{(2)'} = f^{(2)}(x, y^{(1)}, \ldots, y^{(r)}) \\
&\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \\
&y^{(r)'} = f^{(r)}(x, y^{(1)}, \ldots, y^{(r)})
\end{aligned}$$

is calculated in the following way, (Babuska, 1966):

$$\begin{aligned}
&y^{(i)}_{n+1} = y^{(i)}_n + h.\left(\frac{1}{6}k^{(i)}_1 + \frac{1}{3}k^{(i)}_2 + \frac{1}{3}k^{(i)}_3 + \frac{1}{6}k^{(i)}_4\right),\ i = 1, 2, \ldots, r \\
&k^{(i)}_1 = f^{(i)}(x_n, y^{(1)}_n, \ldots, y^{(r)}_n), \\
&k^{(i)}_2 = f^{(i)}(x_n + \frac{1}{2}h, y^{(1)}_n + \frac{1}{2}k^{(1)}_1, \ldots, y^{(r)}_n + \frac{1}{2}k^{(r)}_1), \\
&k^{(i)}_3 = f^{(i)}(x_n + \frac{1}{2}h, y^{(1)}_n + \frac{1}{2}k^{(1)}_2, \ldots, y^{(r)}_n + \frac{1}{2}k^{(r)}_2), \\
&k^{(i)}_4 = f^{(i)}(x_n + \frac{1}{2}h, y^{(1)}_n + \frac{1}{2}k^{(1)}_3, \ldots, y^{(r)}_n + \frac{1}{2}k^{(r)}_3).
\end{aligned}$$

2.4 Simulation

In order to determine mean quantity of constant of parachute apparent air mass, K, a complex of parachute force calculations were done according to the represented methodology with different values of C = 3-18. These simulation results are shown in “Fig. 2” as function of parachute force reducing coefficient $X_1 = (V^{Fx}/V_o)^2$ versus mass ratio $R_m = \rho\,(C_D S)_o^{3/2}/m_c$ and compared with the test results (Knacke, 1996) for numerous parachute tests.

The comparison of calculations and experimental results shows that the best coincidence of them is ensured when K = 0.66, “Fig. 2”, which is recommended as the average value of constant of apparent parachute air mass.

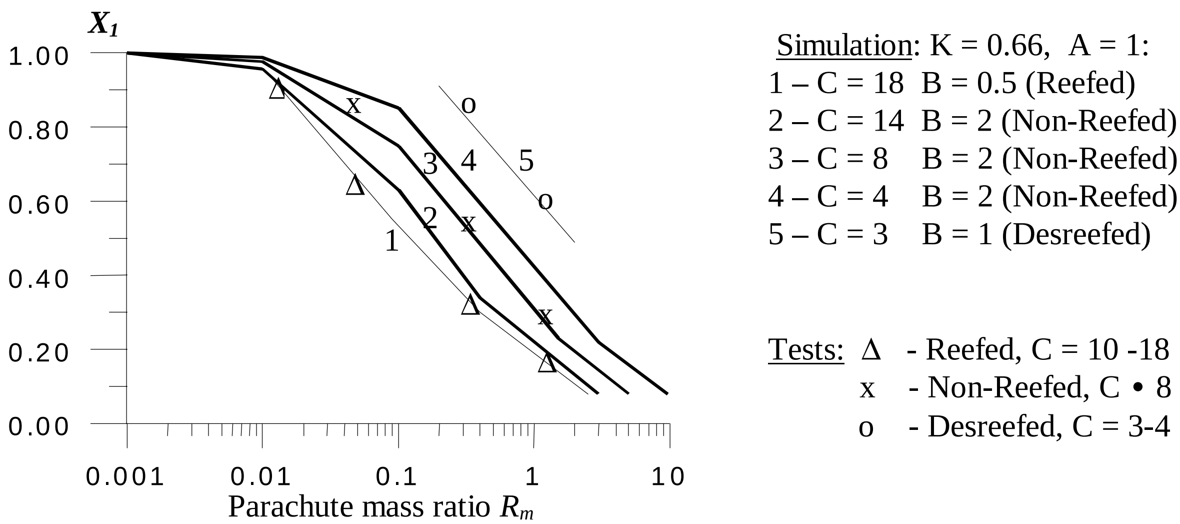


Figure 2 - Computed and measured results of parachute force reduction coefficient X_1

3. ELASTIC PARACHUTE MOTION AND WAKE RECONTACT

In this model we submit for consideration the payload (capsule), the parachute and the added air as individual and interacting objects with mass m_c, m_p, m_a ,“Fig. 3”.

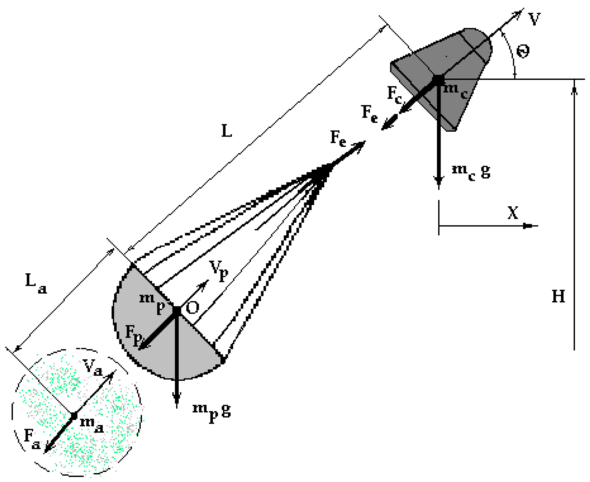


Figure 3 - Model of elastic parachute motion

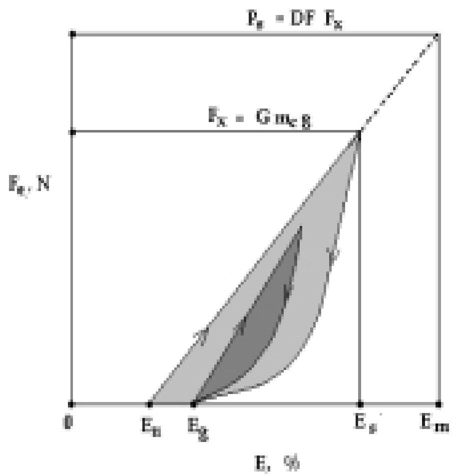


Figure 4 - Model of parachute elasticity

The motion of interacting masses m_c, m_p, m_a is described by following equations:

$$m_c\, V/dt = -\, F_e - F_c - (m_c\, g\ \sin\theta) \quad (33)$$

$$m_p\, V_p/dt = F_e - F_p - (m_p\, g\ \sin\theta) - d(m_a V_p)/dt \quad (34)$$

$$m_a{}^{Fx}\, V_a\, /dt = -\, F_a \quad (35)$$

$$dH\, /dt = V \sin\theta \quad (36)$$

$$dx\, /dt = V \cos\theta - V_w \sin\beta \quad (37)$$

$$dL\, /dt = V - V_p \quad (38)$$

$$dL_a\, /dt = V_p - V_a \quad (39)$$

$$d\theta\, /dt = -(g \cos\theta)/\, V \quad (40)$$

where m_c,m_p,m_a - mass of capsule, parachute and added air, kg
V, V_p,V_a - velocity of capsule, parachute and added air, m/s
V_w - wind velocity, m/s
F_c,F_p,F_a - drag force of capsule, parachute and added air, N
F_e - elastic force (stretching resistance) in suspension lines, N
θ - angle between velocity of capsule and horizon, rad
β - angle between projection of capsule velocity to horizon and wind velocity.

The parachute mass is lumped on the axis of parachute symmetry at the point O of the canopy edge zone and is connected with the capsule mass by the elastic structure (suspension lines) with the length l_s and elasticity E_s. Stretching resistance of suspension lines, F_e, depends on lines strength P_s and its maximum lengthening E_m as shown in “Fig. 4”.

Stretching resistance of suspension lines for first cycle increased load- elongation can be determined as:

$$F_e = k_s\, (L - l_s(1+E_n)), \quad (41)$$

where F_e - stretching resistance of suspension lines, N
k_s - spring constant of lines, N/m
L - canopy point O distance from capsule, m
l_s - suspension lines length, m
E_n - nominal specific elongation at beginning of load increase, non-dimensional.

Spring constant of lines can be determined after the formula:

$$k_s = P_s/\, (l_s\, (E_m - E_n)) = DF\, G\, m_c\, g/(l_s\, (E_m - E_n)), \quad (42)$$

where P_s - lines strength, N
E_m - specific elongation at maximum load of lines strength, non-dimensional
DF - design factor, non-dimensional.

The added air volume m_a/ρ is considered as a sphere with the center at the point O. The size of this volume is proportional to the canopy diameter D_p and changes during inflation.

During parachute motion the added air mass is constantly renewed by the running-over airflow and comes down from the canopy, forming the wake or the pursuing stream. This wake is dragged then by the surrounding air and is dissipated in space. The wake intensity is determined by specific parachute impulse which depends on the canopy diameter and its velocity V_p. Specific parachute impulse has the maximum value when the parachute force is in its maximum. In this case the wake recontact is modeled as the succession of the following processes:

- added air mass coming out from the canopy when the opening force is in its maximum at the moment t_{Fx} ,“Fig. 5”;

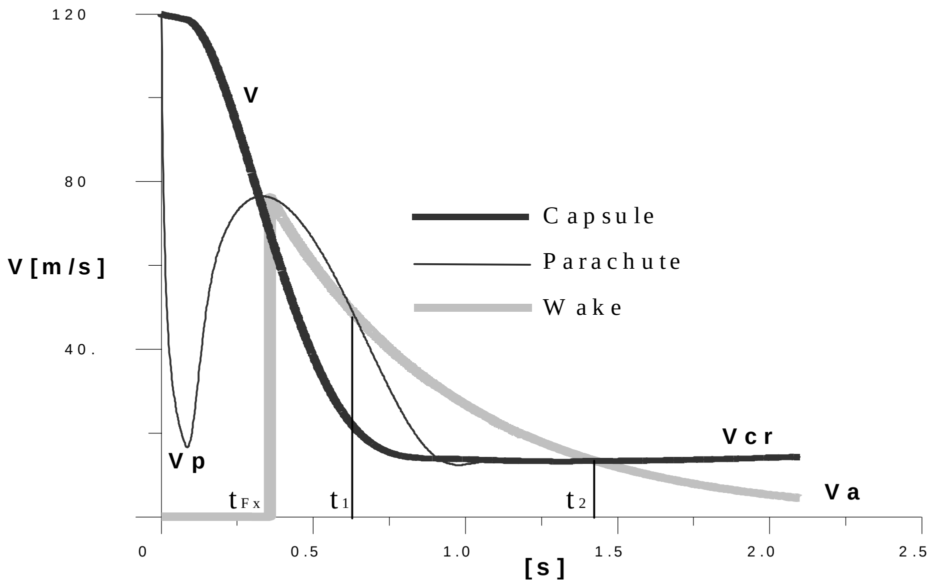


Figure 5 - Velocity of capsule, parachute and wake during inflation and wake recontact

- independent motion of the wake with velocity V_a and volume m_a^{Fx}/ρ under influence of surrounding air by force F_a ;
- wake recontact (if it occurs during time interval from t_1 to t_2) when wake velocity V_a is more than canopy velocity V_p ,“Fig. 5”;
- change of the flow velocity near the canopy and change of the parachute force.

At the beginning of the wake recontact the distance between the canopy and the center of air mass m_a^{Fx}, L_a, is equal to radius of wake volume R_a. Within this the recontact impulse is determined by the parachute velocity and current added mass m_a. When this distance $L_a = 0$, the recontact impulse has its minimum which is determined as the vector sum of the present canopy impulse and of overtaking wake impulse:

$$(m_a V_a)_{min} = m_a V_a(t) - m_a^{Fx} V_a^{Fx}(t), \qquad (43)$$

Independent motion of the wake under influence of friction force with surrounding air can be determined by wake friction coefficient C_f.

With the aim to determine mean quantity of wake friction coefficient C_f, some of simulations were done according to the represented methodology when $K = 0.66$, $A = 1$, $B = 2$ and with different meanings of $C = 6$ -14.

The calculated time functions of parachute drag coefficient during canopy inflation and wake recontact for $C = 10$, $S = 27$ m^2, m_c =150 kg are shown in “Fig. 6”.

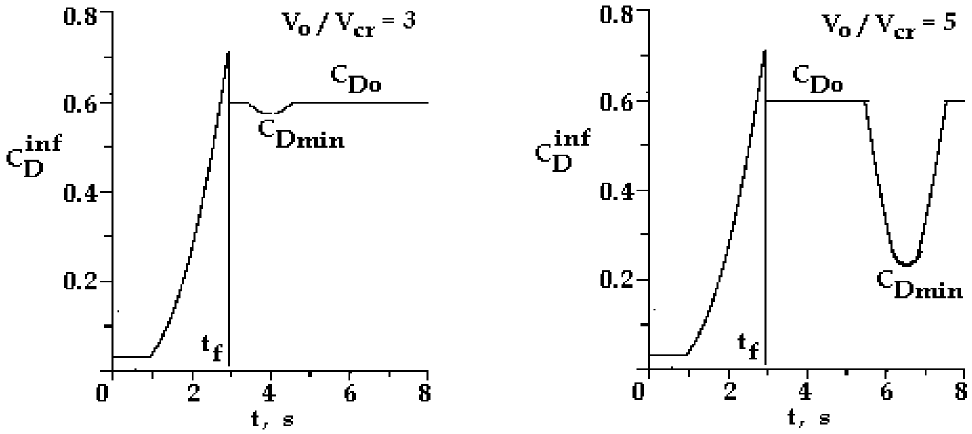


Figure 6 - Parachute drag coefficient during canopy inflation and wake recontact

C_f parameter changed in the range from 0.02 up to 0.06. And at each range the parameter C_D^{inf} as the wake influence characteristic over the parachute was determined as ratio of the minimum drag coefficient C_{Dmin} to settled drag coefficient for full open parachute C_{Do}:

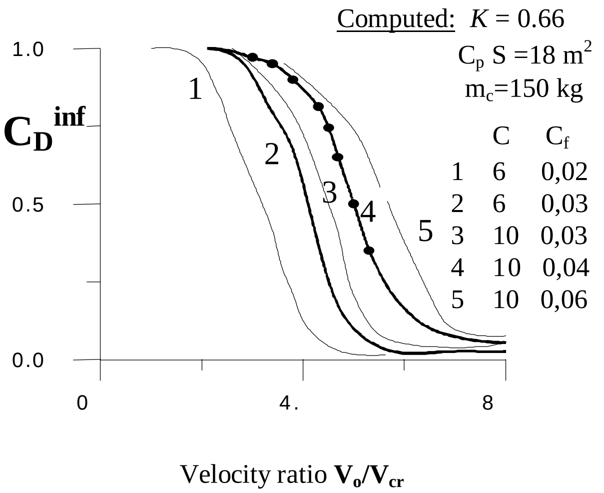
$$C_D^{inf} = F_{D\,min} / (C_{Do}\, q\, S) = C_{Dmin}/C_{Do} \tag{44}$$

where $F_{D\,min}$ - parachute minimum drag force during wake recontact, N.

Results of C_D^{inf} simulations as function of V_o/V_{cr} are shown in “Fig. 7”. These simulations results were compared with the test results (Strickland, 1996) for non-reefed ringslot parachute (20% of porosity, C •10; V_o/V_{cr} = 3-6, R_m = 0.5-3; D_p = 3.3 m). The comparison of calculations and experimental results show that the best coincidence of them is ensured when C_f = 0.04, which is recommended as the average value of the wake friction coefficient.

These results show that the velocity ratio V_o/V_{cr} in excess of 4-6 produces canopy collapse which is based on the occurrence of wake velocities that approach to those of the velocity of the parachute. The bigger C, the higher ratio V_o/V_{cr}.

The analogous results (V_o/V_{cr} > 4.8-5.7) were obtained with the help of the numerical method for the wake recontact based on turbulent wake model (Strickland & Macha, 1990, Strickland & Higuchi, 1996).



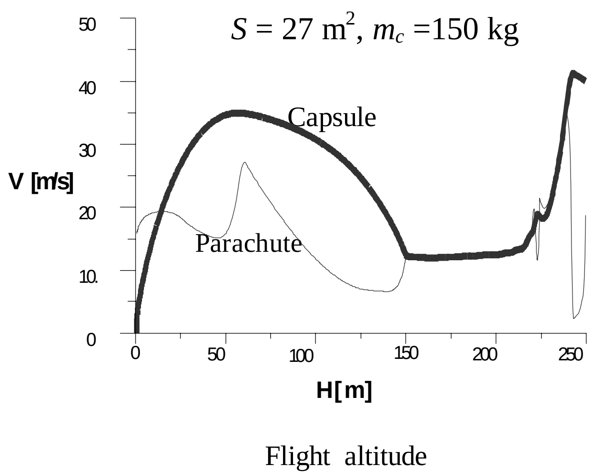


Figure 7 - Wake influence parameter C_D^{inf}

Figure 8 – System dynamics with elastic riser

Calculation results of velocity of capsule and parachute during space motion of system with elastic riser (K = 0.66, A = 1, B = 2, C =10, C_f = 0.04) are shown in "Fig. 8".

4. CONCLUSIONS

The dynamics of high performance parachutes as part of a ground recovery system for small returnable orbital payloads has been extensively investigated.

The work considered mainly modeling and simulation features of the system, and the proposed dynamic models comprise an elastic parachute with apparent air influence.

The article presented the mathematical description and the numerical solution of the parachute dynamics during its motion along a trajectory. The method took under consideration specific features, such as wake re-contact and parachute elasticity.

A very good agreement between theoretical results and experimental data could be achieved in the present work. The paper showed and discussed the results of the system motion simulation and tests.

Acknowledgements

The first author would like to express his gratitude to CNPq for supporting him as visiting scientist (Grant No. 300.186/96-7) at the Space Systems Division of the Instituto de Aeronáutica e Espaço, Centro Técnico Aeroespacial.

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