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Dynamical Analysis of Jettison Piloting for Air Bomb with Bomblets

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ABSTRACT

The main parachutes drawn down by a pilot parachute is the generally used method of the jettison of air bomb with bomblets and their interaction process is the basis and key for the bomb projection. A mechanical model loaded by the string of pilot parachute is theoretically established, and under different projection velocities, the design method of the length and strength for the string of the pilot parachute is suggested. The results show that for a certain 500 kg air bomb, if the projection velocity is 222 m/s and the strength of the string is 5000 N, the length of the string 3 m cannot meet the requirement.

Keywords: Air bomb, air-delivered weapon, retarding parachute, weapon with submunitions

1. INTRODUCTION

Jettison is one of the key procedures of air bomb projection, and its reliability directly affects the accuracy of target points and the normal performance of warheads. Different jettison types have different reliabilities. The way that the main retarding parachutes are drawn down by the pilot parachute is the generally used method for the jettison process[1]. An air bomb has two or more bomblets, each bomblet has a retarding parachute and its jettison is realised by the tension when the retarding parachute is inflated.

There are many research reports[2-4] concerned with the retarding parachute ballistics and the materials. The reliability analysis of a jettison process is related to the projectile trace of the bomb, and also to the interaction between the bomb and the parachutes and its intensity calculations, however, being studied by fewer workers. Prevorsek[5], *et al.* analysed the parameters of parachute string when the parachute was inflated, from a point of view of materials science, and introduced an experimental method to measure these parameters. They put emphasis on properties of string materials and problem that the string absorbs the impact energy. In this study, the dynamical process in which the pilot parachute pulls the main retarding parachute, and the reliability, are analysed. In the process of pilot parachute action, in consideration of the load exerted on its string, the strength and the deformation, a method to determine the parameters of pilot parachute string under different projection velocities is presented .

2. PILOT PARACHUTE & CLOSED MAIN PARACHUTE

2.1 Load of Pilot Parachute String

When the bomb is thrown out of the aircraft, its velocity includes two components in which one is along the horizontal direction, approximately equal to the velocity of aircraft flight, and the other describes the vertical motion. After some

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time, the trail of the mother bomb is opened by a certain mechanism, the pilot parachute is forced to throw out. If only one bomblet is considered, since its retarding parachute is linked with the pilot parachute through a pilot string, after the pilot parachute is inflated, the string is straightened by the pull, then pulling the main parachute. After the main parachute is pulled out from the cabin of the mother bomb, it is inflated and decelerated to pull out the bomblet.

At the initial moment when the mother bomb is thrown out, its vertical velocity is zero, and the horizontal velocity is equal to that of the aircraft flight, generally about 200 m/s. This process, by which the mother bomb is thrown out of the aircraft cabin until its jettison, will take a period of time less than 1 s, while the total projection process generally needs several tens of seconds. Since there is an air drag, at some moment, the vertical velocity of the mother bomb is less than that calculated from the motion of a free-fall body. According to the equation of motion of a free-fall body, after 1 s later the mother bomb leaves off the aircraft, its vertical velocity is V_v = 3 m/s, quite less than its horizontal velocity $V_L \approx$ 200 m/s. Therefore, it may be regarded as the pulling process caused by the pilot parachute inflating mainly as one that overcomes the horizontal motion. If the position that the pilot parachute is inflated is assumed as point zero, as shown in Fig. 1, at this moment, the pilot string is straightened by the pull and is subjected to load. This load gradually increases until the velocity of the pilot parachute is equal to that of the closed main parachute. The relative motion between the main parachute and the mother bomb makes the parachute pulled out from the mother bomb case.

2.2 Motion Drag of Pilot Parachute

The effective diameter of the pilot parachute may be solved by the following equation:

$$\pi d^2 / 4 = Sh \tag{1}$$

where d, S and h are the effective diameter of the pilot parachute, the action area of the pilot parachute, and the thickness of the pilot parachute, respectively.

The Reynold's number is:

$$R_e = V_g d\rho / \mu \tag{2}$$

where V_g is the velocity of the pilot parachute, ρ is the density of air (ρ = 1.25 kg/m^3), and μ is the coefficient of dynamic viscosity ($\mu = 1.77 \times 10^{-5}$ Ns/m^2). In this work, a certain 500 kg air bomb is taken as the studied example. It is given that the area of the pilot parachute, S = 0.378 m^2, the thickness $h = 3 \times 10^{-3}$ m, and the velocity $V_g \approx$ 100~200 m/s, and than one has:

$$R_e = (0.27 \sim 0.54) \times 10^4$$

It is known from the theory of fluid mechanics that when $500 \le R_e \le 2 \times 10^5$, the viscous friction drag of the fluid can be neglected and only the differential pressure is considered. Thus, the

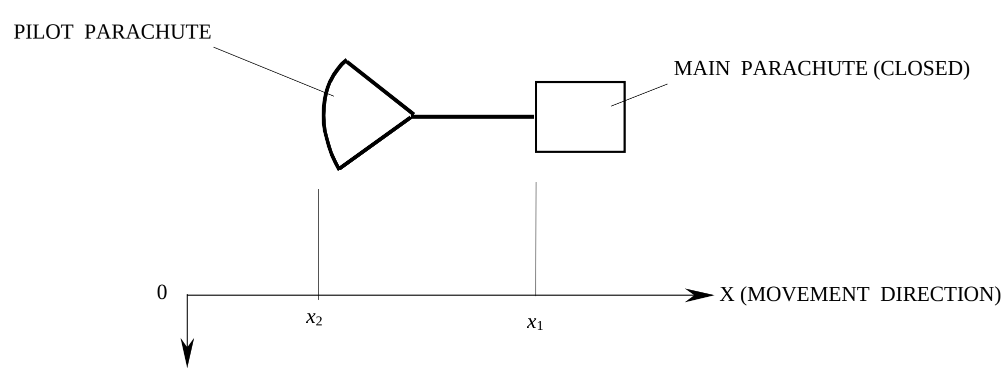

Figure 1. Movement situation of pilot parachute and main parachute

drag exerted on the pilot parachute may be expressed as

$$R = K_r V_g^2 \tag{3}$$

where R is the drag exerted on the pilot parachute, K_r is a coefficient. In this study, the experimental results show that K_r = 0.7.

2.3 Relationship between Deformation & Load for Parachute String

The string of the pilot parachute, which is made up of the synthetic fibre with excellent elasticity, may be regarded that its deformation will follow a linear relationship with the load, is given by

$$F = \frac{[F]}{[\delta]}\delta \quad \text{or} \quad F = K_{rope}\delta \tag{4}$$

where F is the load along the parachute string, $[F]$, $[\delta]$ and δ are the limit load of the string, limit tensile deformation, and tensile deformation, respectively, in which K_{rope} = $[F]/[\delta]$.

If the position at which the pilot parachute is inflated is assumed to be point zero, after time t, the pilot parachute is located at x_2 and the main parachute at x_1, obviously, one has:

$$x_1 - x_2 - l = \delta \tag{5}$$

where l is the length of the pilot parachute string. Assuming that x_{de} denotes the transient displacement of the main parachute when the load is exerted on the pilot parachute string, and x_g is the transient displacement of the pilot parachute in this process, thus, $x_{de} = x_1 - l$ and $x_g = x_2$. It can be found that $\delta = x_{de} - x_g$ and then from Eqn (4), one has:

$$F = K_{rope}(x_{de} - x_g) \tag{6}$$

2.4 Interaction Between Pilot Parachute & Main Parachutes

For the inflated pilot parachute, it satisfies that

$$m_g \frac{dV_g}{dt} = F - R \tag{7}$$

where m_g is the mass of the pilot parachute, and V_g is the transient velocity of the pilot parachute.

In fact

$$V_g = \frac{dx_g}{dt}$$

Substitution of Eqns (6) and (7) into Eqn (3) yields:

$$m_g \frac{dV_g}{dt} = K_{rope}(x_{de} - x_g) - K_r V_g^2 \tag{8}$$

During the pilot parachute being loaded (the load increasing), the main parachute is being at the closed state and its velocity varies from large to small. Since the air drag is much less than the inertial force for the closed main parachute, it may not be considered and the equation of motion is

$$m_{de} \frac{dV_{de}}{dt} = K_{rope}(x_{de} - x_g) \tag{9}$$

where m_{de} and V_{de} are the mass and the transient velocity of the main parachute. Equations (8) and (9) include four unknown parameters V_g, V_{de}, x_{de} and x_g, and therefore the other two equations are required to solve these parameters. At this moment when the pilot parachute opens, its velocity is approximately equal to zero, and so in the process that the pilot parachute string is loaded, the energy equation is given by

$$\int_0^{x_g} F dx_g - \int_0^{x_g} K_r V_g dx_g = \frac{1}{2} m_g V_g^2$$

or

$$\int_0^{x_g} K_{rope}(x_{de} - x_g) dx_g - \int_0^{x_g} K_r V_g dx_g = \frac{1}{2} m_g V_g^2 \tag{10}$$

where V_{de0} is the velocity of the main parachute at the moment that the pilot parachute string starts to be loaded. Similarly, for the main parachute, the energy equation can be given by

$$\frac{1}{2}m_{de}V_{de}^2 + \int_0^{x_{de}} F dx_{de} = \frac{1}{2}m_{de}V_{de0}^2 \tag{11}$$

From the above four equations, the four unknown parameters V_g, V_{de}, x_{de} and x_g can be solved. However, these four equations form an integral equation group, which is difficult to be solved. To be convenient for analysing this problem, some simplifications will be taken in the study.

3. STRENGTH ANALYSIS OF PILOT PARACHUTE STRING

3.1 Peak Acceleration of Main Parachute

From Eqn (9), one may have:

$$m_{de}\frac{dV_{de}}{dt} = K_{rope}(x_{de} - x_g) = K_{rope}\delta \tag{12}$$

From Eqn (12), it can be seen that when the strength and deformation properties of the pilot parachute string are given, the acceleration of the main parachute $\frac{dV_{de}}{dt}$ will increase as the tensile deformation of the pilot parachute string rise. To guard that the pilot parachute successfully pulls out the main parachute, it should be

$$\delta \le [\delta] \tag{13}$$

where $[\delta]$ is the limit tensile deformation of the pilot parachute string.

From Eqns (12) and (13), one has:

$$\frac{dV_{de}}{dt} \le \frac{K_{rope}}{m_{de}}[\delta]$$

Thus, $(K_{rope}/m_{de})[\delta]$ is the peak acceleration of the main parachute, and it can be rewritten as:

$$\left.\frac{dV_{de}}{dt}\right|_{\max} = \frac{K_{rope}}{m_{de}}[\delta]$$

Considering Eqn (4), one may yield

$$\left.\frac{dV_{de}}{dt}\right|_{\max} = \frac{[F]}{m_{de}}$$

For the 500 kg air bomb discussed in this work, the strength of the pilot parachute string $[F]$ = 50000 N, and the mass of the main parachute m_{de} = 24 kg. Therefore, it can be found that

$$\left.\frac{dV_{de}}{dt}\right|_{\max} = 2080 \text{ m/s}^2$$

Because of the damping action of the pilot parachute string, in loading, the acceleration of the pilot parachute must be less than that of the main parachute.

From Eqn (8), it can be given that

$$K_{rope}(x_{de} - x_g) = m_g\frac{dV_g}{dt} + K_r V_g^2 \le m_g\frac{dV_{de}}{dt} + K_r V_g^2$$

This equation can also be expressed as

$$K_{rope}(x_{de} - x_g) \le m_g\left.\frac{dV_{de}}{dt}\right|_{\max} + K_r V_g^2$$

where

$$m_g\left.\frac{dV_{de}}{dt}\right|_{\max} + K_r V_g^2$$

is the maximum load exerted along the pilot parachute string, that is:

$$F_{\max} = m_g\left.\frac{dV_{de}}{dt}\right|_{\max} + K_r V_g^2$$

It is given that the mass of the pilot parachute m_g = 24 kg, $F_{\max}$ = $[F]$ = 50000 N, and the damping coefficient k_r = 0.7. From Eqn above, one obtains:

$$50000 \ge 0.87 \times 2080 + 0.7\ V_g^2 \tag{14}$$

It can be solved, the maximum velocity of the pilot parachute is:

$$V_g \leq 262 \text{ m/s}$$

From the above analysis, it can be seen that if the flight velocity of the aircraft is less than 262 m/s when the mother bomb is thrown out, the pilot parachute and its string can successfully pull out the main parachute. Similarly, for the given 500 kg air bomb, under different strengths of the pilot parachute strings, the maximum velocities which the pilot parachutes can tolerate are given in Table 1.

If the flight velocity of the aircraft is given when the mother bomb is thrown out, it is necessary to choose the strength of the pilot parachute string based on the results listed in Table 1. The higher the velocity when the aircraft throws the bomb, the higher strength of the pilot parachute string is chosen. If the velocity of the aircraft during flight is beyond the limit value in Table 1, one must choose the pilot parachute string so long that it can provide a damping action to meet the requirement of strength.

Table 1. Maximum velocities of pilot parachute enduring under different string strengths

Strength of the string [F] (N)	5000	15000	25000	35000	45000
Maximum velocity [V_g] (m/s)	83	144	186	219	249

4. LIMITATION OF TENSILE DEFORMATION FOR PILOT PARACHUTE STRING

The limit strength of the pilot parachute chosen from Table 1 is one of the conditions which insures that the main parachute can be pulled out by the pilot parachute. If the velocity of the aircraft during flight is beyond the requirement in Table 1, a suitable length of the pilot parachute string must be chosen to avoid too high acceleration for the motion of main parachute during the loading process after the pilot parachute string is straighten by the pull. It makes the transient velocity of synchronisation motion of the main and the pilot parachutes not to be beyond the corresponding value in Table 1.

From Eqn (9), it may be given that

$$m_g \frac{dV_{de}}{dt} = K_{rope}(x_{de} - x_g) \leq K_{rope} x_{de} \tag{15}$$

So, according to this equation

$$m_g \frac{dV_{de}}{dt} = K_{rope} x_{de} \tag{16}$$

the minimum value of x_{de} is yielded. It can be seen from Eqn (8) that the condition making Eqn (16) right is:

$$x_0 \approx 0, \qquad \delta = x_{de} \tag{17}$$

That is to say, in the loading process of pilot parachute string, the velocity of the pilot parachute is very small (the displacement tending to zero). At this moment, the displacement of the main parachute is the tensile value of the pilot parachute string. Integrating Eqn (16) yields:

$$m_{de}(V_{de0}^2 - V_{de}^2) = K_{rope} x_{de}^2 \tag{18}$$

where V_{de0} is the velocity of the main parachute at the moment that the pilot parachute string starts to load due to its straightening by the pull, and V_{de} is that when the load exerted along the string reaches its maximum (at this time, the velocity of the pilot parachute becomes equal to that of the main parachute). Substituting Eqn (17) into Eqn (18) yields:

$$\delta = \sqrt{\frac{m_{de}(V_{de0}^2 - V_{de}^2)}{K_{rope}}} \tag{19}$$

To decrease the length of the pilot parachute string, the tensile value of the pilot parachute string should reach its limitation. Considering Eqns (4) and (19), one obtains:

$$\delta = \frac{m_{de}(V_{de0}^2 - V_{de}^2)}{[F]} \tag{20}$$

It can be seen that the larger the mass of the main parachute, the higher the tensile value of the pilot parachute string should be, and the larger the limit strength of the string, the smaller its tensile limitation is, ie, the shorter length the string can be taken. If the flight velocity of aircraft is 222 m/s while throwing out the bomb, the maximum velocity that the pilot parachute can tolerate may be found as per Table 1. Corresponding to the value in Table 1, the velocity of the main parachute decreasing from 222 m/s by the pull of the pilot parachute is then calculated using Eqn (14), which is shown in Table 2.

Table 2. Tensile limitation of pilot parachute string

Maximum velocity (m/s)	83	144	186	219	249
Tensile limitation (m)	204	45	14	0.9	--

The tensile rate of the pilot parachute string is generally 30 per cent by which the shortest length of the pilot parachute string that satisfies tensile limitation, can be presented as shown in Table 3. For the given 500 kg air bomb, the design length of the pilot parachute string, 3 m, can meet the requirement. If the chosen limit strength of the string is 500 kg, only its length equal to 680 m can meet the requirement, which shows that it is a case not to come true.

Generally, the length of the pilot parachute string cannot be too long, so that the tensile value of the string is certain. At this time, the limit strength

Table 3. Minimum length of pilot parachute string

Maximum velocity (m/s)	83	144	186	219	249
Minimum length (m)	680	150	47	3	--

of the string may be determined by Eqn (20). Before that, it is necessary firstly to determine the velocity of synchronisation motion for the main parachute and the pilot parachute after the main parachute is pulled.

From Eqn (8), it can be seen that if the strength of the string is given, the larger the acceleration of the pilot parachute, the smaller the calculated maximum velocity that the pilot parachute tolerates. Therefore, when a larger acceleration for the pilot parachute is taken, the theoretical result tends to be safe. Because of elasticity of the pilot parachute, its acceleration is certainly less than or equal to that of the main parachute. Under the condition that the acceleration of the pilot parachute is replaced by that of the main parachute, an estimation of the endurable velocity for the pilot parachute obviously meets the requirement of safety. It can be found from Eqn (12) that

$$\frac{dV_{de}}{dt} = K_{rope}\frac{\delta}{m_{de}} \tag{21}$$

Letting that the inner force of the pilot parachute string is equal to its limit strength, eg

$$K_{rope}(x_{de} - x_g) = [F]$$

and

$$\frac{dV_g}{dt} = \frac{dV_{de}}{dt}$$

combining Eqn (22) with Eqn (8) may yield:

$$[F] = m_g \frac{K_{rope}\delta}{m_{de}} + K_r V_g^2 \tag{22}$$

When a limitation case is taken, given by

$$\delta = [\delta] \tag{23}$$

Eqn (22) may be rewritten as

$$[F] = \frac{K_r V_g^2}{1 - m_g / m_{de}} \tag{24}$$

From this equation, it can be seen that the larger the mass of the main parachute, the higher the strength of the pilot parachute string is, and the larger the velocity that the pilot parachute tolerates, the higher the strength of the pilot parachute string is.

When the pilot parachute string is straightened by the pull until its load reaches the maximum, the velocity of the pilot parachute is equal to that of the main parachute, that is

$$V_g = V_{de} \tag{25}$$

From Eqns (20), (24), and (25), it is easy to derive that

$$m_{de}V_{de0}^2 - m_{de}\frac{[F](1-m_g/m_{de})}{K_r} = [F]\delta$$

or

$$[F] = \frac{V_{de0}^2}{\frac{1}{m_{de}}(\delta - \frac{m_g}{K_r}) + \frac{1}{K_r}} \tag{26}$$

If the velocity of the aircraft at throwing out the bomb, the masses of pilot and main parachutes, the damping coefficient of pilot parachute, and the tensile value of pilot parachute are given, the limit strength of the pilot parachute string can be designed using Eqn (26). For the 500 kg air bomb, V_{de0} = 222 m/s, m_{de} = 24 kg, K_r = 0.7, and m_g = 0.87 kg, and therefore from Eqn (26), one has:

$[F]$ = 35417 N

That is to say, for the 500 kg air bomb discussed in this study, the strength of the pilot parachute string more than 35417 N can meet the requirement of strength.

From Eqn (25), it can be obtained that

$$V_g = \sqrt{\frac{35417(1.00-0.87/24)}{0.7}} = 220.80 \text{ m/s}$$

It shows that when the pilot parachute is straightened by the pull until the synchronisation motion of the pilot and main parachutes starts, the velocities for the two are 220.8 m/s. After that, both travel at the same speed and simultaneously decelerate.

5. STRENGTH ANALYSIS OF PILOT PARACHUTE STRING UNDER ABNORMAL CONDITION

After the pilot parachute is inflated, its string is straightened by the pull until subjected to the maximum load, and since the main parachute is pulled, it produces a relative motion with the bomb. Except for the above analysis, whether this process can be finished normally or not, also depends on the matching between the main parachute packet and the mother bomb case. If the space between these is too small, or the pulled acceleration of the main parachute packet is too large, it is possible to cause a synchronisation motion of the main parachute packet and the bomb at a certain moment. If so, the actual load exerted on the pilot parachute string does not result from the main parachute, but it is from the total bomb. Once the strength of the pilot parachute string is lower, the string breakdown can occur at this instant which will induce that the process of the pilot parachute piloting the main one is failure. Therefore, under abnormal condition, it is necessary to analyse the strength of the pilot parachute string.

In the similar manner to the derivation of Eqn (26), if the bomb becomes the final load after the pilot parachute string is straightened by the pull, and it starts to be subjected to a load, the pilot parachute has the same velocity as the mother bomb. Thus, one has:

$$[F] = \frac{V_{de0}^2}{\frac{1}{m_m}(\delta - \frac{m_g}{K_r}) + \frac{1}{K_r}} \tag{27}$$

where m_m is the mass of the mother bomb. Substitution of the parameters as the final load related to the bomb into Eqn (27) yields the value of $[F]$, which is quite close to the [F] from the main parachute as the final load. Since the inertia increases, if the duration is too long for the motion of the pilot parachute and the bomb at the same velocity, it can be beyond the maximum velocity that the pilot parachute string can tolerate at some instant, due to the bomb accelerating in the vertical direction. In this case, the pilot parachute or its string may be damaged.

6. CONCLUSIONS

The larger the flight velocity of the aircraft at the time of bomb throwing, the higher the strength of the pilot parachute string should be. When its strength is given, the larger the mass of the main parachute, the longer pilot parachute string is required. If it is very high for the string to be able to tolerate the velocity (larger than or equal to the fight velocity when the aircraft throws out the bomb), the limit strength of the pilot parachute is insensitive to its final load. For the given 500 kg air bomb, the strength of the pilot parachute string 50000 N can meet the requirement. If the strength is 5000 N, the length of the string should be 680 m to meet the requirement. When its length is 3 m, the string will certainly break, which is in agreement with the results obtained. The project has been proved by the experiments. The two pilot parachute strings were used in the experiments, and their strengths were 25000 N and 50000 N. The pilot parachute string of 25000 N strength and the pilot parachute string of 50000 N strength worked successfully in the experiments.

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