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Numerical Analysis of a PRD for a Tethered Lighter than Air Vehicle

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Abstract
This paper presents the results of simulation studies carried out using CAE softwares. In this simulation, the trajectory and velocity of descent of the payload after tether breakage under various operating conditions are estimated. Results are reported for a lighter than air vehicle with spherical shaped envelope consisting of a double chamber. The results indicate that the terminal velocity attained by the envelope is independent of the initial altitude of deployment and hole diameter, but is a strong function of the volume of undeflated chamber of the envelope. The amount of drift from deployment location, however, depends on the size of the hole created, and initial altitude of deployment.

Keywords: Lighter than air vehicle, Payload Recovery Device, Double Chamber Envelope, Terminal Velocity

Introduction

A Lighter than air vehicle is an aerodynamically shaped envelope filled with a Lighter-Than-Air (LTA) gas and tethered to the ground. One of the main operational problems faced by an lighter than air vehicle when deployed at a site is accidental breakage of tether, which results in drifting of its payload. In such cases, a Payload Recovery Device (PRD) is activated, and the recovery of payload is accomplished in three stages, viz., tether breakage detection, signal transmission and device activation. The lighter than air vehicle envelope is deflated by deploying a mechanism that results in creating a circular hole of appropriate size on the top portion of the envelope.

An aerostat is a Lighter-Than-Air (LTA) system comprising of a light-weight envelope filled with a light gas like Helium or Hydrogen to create sufficient buoyancy and is used to carry a payload attached to it at a pre-decided altitude. Aerostats have found widespread applications like military surveillance and antisubmarine warfare [1], regional civilian road traffic monitoring, carrying a payload of communications, reconnaissance or meteorological equipment, for advertising, and carrying video equipment and digital cameras. Aerostats are tied to the ground with a tether to prevent them from drifting away due to the free lift, which refers to the net difference between the upward thrust (buoyancy) provided by LTA gas and the total weight of the aerostat system. In aerostat design, around 15% free lift is generally provided, which is balanced by the tension in the tether. Free lift helps the tether to remain taut; in the absence of which the tether would become slack and aerostat might descend downwards due to slight decrease in density of surrounding air as temperature increases.

Need For Payload Recovery Device

The tether is the only connecting link between the ground and aerostat. During deployment of an aerostat, accidental breakage of tether is always a possibility due to a variety of reasons. The aerostat would then start ascending due to free lift and drift away due to horizontal winds, which would result in loss of platform and the expensive payload mounted on it, further, the drift could also endanger other airborne systems in its vicinity. Therefore, there is a need to design a Payload Recovery Device (PRD) which recovers the aerostat and payload safely to the ground in some accessible vicinity. One such PRD was designed by Bhat and Pant [2] which is described in the next section.

Details of PRD Mechanism

The mechanism consists of three phases: tether breakage detection, signal transmission and device activation, as shown in Figure 1.

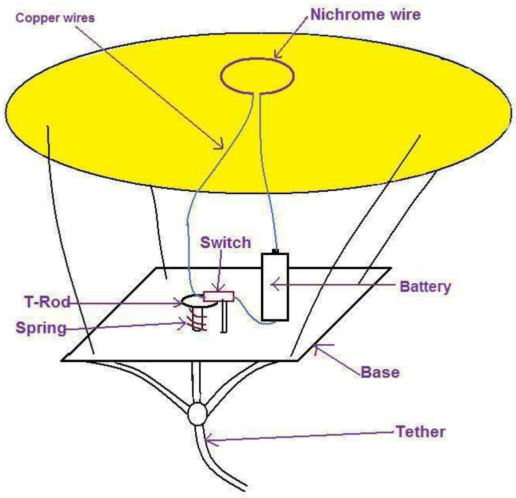

Fig. 1: Schematic diagram of Payload Recovery Device (PRD) [2]

The PRD consists of three basic components, which are described below.

A. Tether breakage detection

The mechanism used to detect tether breakage consists of a Push Rod around which a helical spring is wound. A lug is soldered at the bottom of the Push Rod to which tether can be attached. Twisting of tether is prevented by allowing free rotation of Push Rod about its axis. When the tether exerts tension on the Push Rod, it is pulled downwards and the spring gets compressed. And when the tether breaks, as the tension no longer acts, the restoring force of the spring pushes the Push Rod upwards.

B. Signal transmission

An electric switch is placed just above the face of the Push Rod. So when the Rod is pushed upwards, its face can be used to turn on the switch. This switch is a part of a circuit that consists of a rechargeable battery and a Nichrome wire, which is attached on top of the envelope. All other connections are made with copper wires. The switch remains in off position until the Push Rod turns it on, and once it is turned on, the circuit gets completed.

C. Device Activation

The mechanism is based on the Joule's principle of heating, i.e., current passing through a heater wire generates heat. The wire would be attached on top of the envelope in a circle, so that the heat generated would melt a circular hole in the envelope. For testing the mechanism, a Nichrome wire was used and the envelope was made of PVC. Nichrome wire would work as long as the envelope material has a low melting point of around 100-350 0C, for higher temperatures, wires that generate higher temperatures can be used. For example, Kanthal wires can be heated to a temperature of at least 11000 C [3]. When the heated Nichrome wire melts the hole in the PVC envelope, the gas contained in the envelope escapes slowly, and hence the buoyancy reduces. Due to this, the aerostat gradually descends to the ground and the payload is recovered. The size of the hole would determine the leak rate of gas and hence the velocity of descent of the aerostat.

In order to reduce the velocity of impact, the aerostat envelope can be constructed of two chambers, viz., the major chamber and the minor chamber separated by a gas-tight fabric. The major chamber would be located below, and would be larger in volume. The volume of major chamber would be such that the upward thrust provided by the gas inside it would be slightly lesser than the weight of the aerostat. The aerostat would be able to lift only when both the chambers are filled with gas and not if one of the two chambers were deflated. Such two chamber envelopes have been used in the past for various other applications [4].

Critical Review of Initial Simulation

It is quite intricate to mathematically calculate the velocity of descent when it strikes the ground because after the tether breaks and the hole is made in the envelope, gas escapes continuously from it. So at each instant the mass of the aerostat reduces, and also the buoyancy force of the gas remaining reduces. As a result, the acceleration and the velocity of the aerostat system also changes continuously. Bhat and Pant [2] have developed a MATLABTM code for simulation of the motion of the aerostat envelope after activation of PRD, to evaluate the velocity of descent. This simulation evaluates the force, acceleration, velocity and altitude of the aerostat iteratively after small interval (0.02 seconds), till the aerostat lands on the ground.

This simulation code was critically reviewed and the following shortcomings were identified in it, which mainly relate to the simplifying assumptions made in it:

1) It was assumed that the internal pressure variation has no significant effect on the leak rate of gas; hence the leak rate remained constant. The leak rate was evaluated as the product of velocity of rise of gas and the cross-sectional area of the hole. In reality, the leak rate would be larger in the initial stages and would decrease slightly as the pressure decreases. However, it would be difficult to calculate the leak rate accurately as the internal pressure does not change linearly with the volume of gas remaining inside the envelope because the aerostat envelope shrinks.

2) The density of air and gas inside the envelope was assumed to remain constant throughout the flight of the aerostat, which was a valid assumption only for aerostats deployed at low altitudes.

3) A constant value of Drag Coefficient was assumed throughout, although it is likely to change due to change in shape as the envelope shrinks. On the same lines, it was assumed that the projected area of the aerostat envelope remained the same during its descent, which is definitely not the case the envelope kept shrinking.

Simulation Using Open Source Software Scilab

In order to obtain more accurate results, an attempt was made to remove some of the abovementioned assumptions made in the previous simulation. The enhanced simulation code was developed in SCILAB open source software. The MATLABTM code was modified by adding variables for drag co-efficient, projected area and pressure, and simulation results were obtained for a double chamber envelope.

The process of gas leaking out of the envelope is modelled as an Adiabatic Process which is a valid assumption for a process taking place in an extremely short span of time and the pressure difference is also not so high. The simulation was carried out by considering drag co-efficient, projected area and pressure inside the envelope as a function of volume remaining at each instant.

The initial velocity of the escaping gas immediately after the hole is created is due to the pressure difference and is given by Eq. (1) as

$$V = \sqrt{(2 * (P - P_{atm})/\rho} \quad (1)$$

Where,

V	Initial velocity of the gas
P	Initial Pressure inside the aerostat
P_{atm}	Ambient Pressure
ρ	Density of the gas

For an adiabatic process, $PV^{\gamma} = \text{Constant}$ (2)

By differentiating and re-arranging the terms, the pressure inside the envelope is obtained from the equation below.

$$P_{(t+\Delta t)} = P_{(t)} * ((\gamma + 1) * Vol_{(t)} - \gamma * Vol_{(t+\Delta t)})/Vol_{(t)} \quad (3)$$

Where,

$P_{(t+\Delta t)}$	Pressure inside the aerostat at time t+Δt
$P_{(t)}$	Pressure inside the aerostat at time t
γ	Ratio of specific heats of the gas
$Vol_{(t+\Delta t)}$	Volume of gas inside the aerostat at time t+Δt
$Vol_{(t)}$	Volume of gas inside the aerostat at time t

Results of the Simulation for Double Chamber Envelope

In this section, we present some results obtained in the simulation of a double chambered spherical shaped aerostat envelope after the PRD is triggered. Table 1 lists the basic data related to the aerostat.

Table 1: Basic data of the Aerostat

Parameters	Value
Volume of the envelope	100 m^3
Projected Area of the envelope	132 m^2
Initial Drag Co-efficient	0.15
Fixed Weight of Aerostat	80.64 Kg
Time Lag between tether breakage and hole formation	5 s

Table 2 lists the velocity and time of descent obtained for various volumes of the un-deflated chamber, if the radius of the hole is 20 cm. It is seen that the time of descent and the velocity of descent decreases as the volume of un-deflated chamber increases. Similar results were observed in the case of larger hole radii as well.

Table 2: Results for hole diameter of 20 cm

Volume of the un-deflated chamber (m^3)	Velocity of Descent (m/s)	Time of Descent (s)
40	14.097	40.95
50	11.72	43.45
55	10.32	45.9
60	8.71	50.25
65	6.72	59.95
70	3.81	98.81

The three basic parameters that can affect the time of descent and velocity of descent of an aerostat envelope after the PRD is activated are the initial altitude of deployment, radius of the hole, and volume of the un-deflated chamber. Results of simulation for these three parameters are presented in the next section.

A. Initial altitude of deployment (h)

The effect of initial altitude on the time and velocity of descent for volume of un-deflated chamber of 50 m3 is shown in Fig. 2(a) and (b), respectively. The aerostat is seen to rise by around 15 m due to free lift, and then slowly start descending at a constant rate. It can also be seen that the initial altitude does not affect the velocity of descent, which reaches a terminal velocity of around 2 m/s after around 100 iterations in all cases, which corresponds to around 5 seconds after breakage.

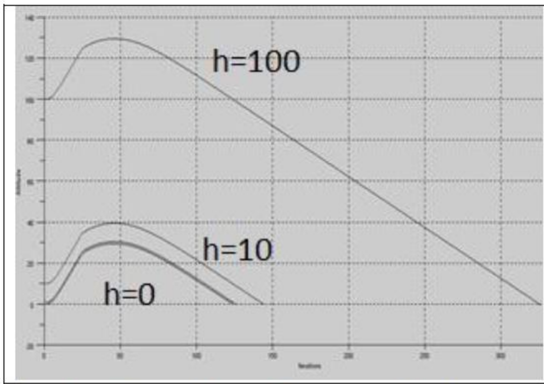

Fig. 2(a): Time of Descent for various altitudes

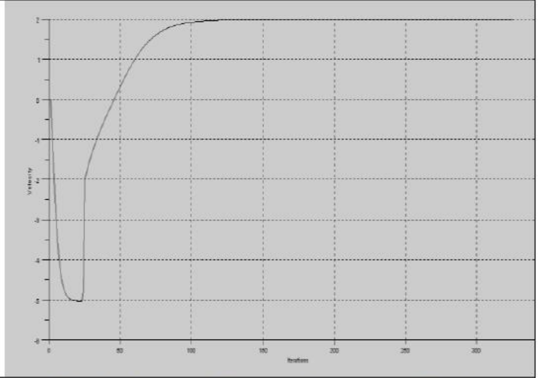

Fig. 2(b): Velocity of Descent for various altitudes

B. Effect of hole radius (r)

The effect of hole radius on the time and velocity of descent for volume of un-deflated chamber of 50 m3 is shown in Fig. 3(a) and (b), respectively. It can be seen that the altitude to which the aerostat rises due to free lift is increased as the hole radius is decreased, and then it starts sinking at a fixed rate. Further, the hole radius does not affect the final velocity of descent, which reaches a terminal velocity in all cases.

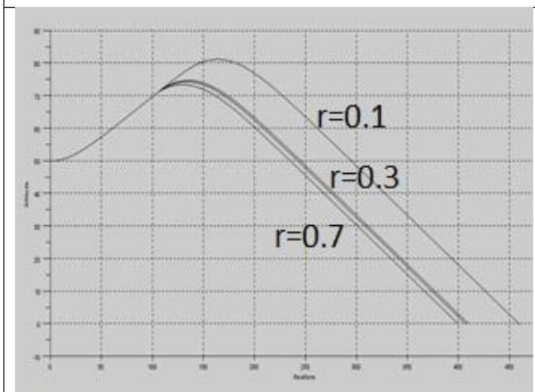

Fig. 3(a) Time of descent for various hole radii

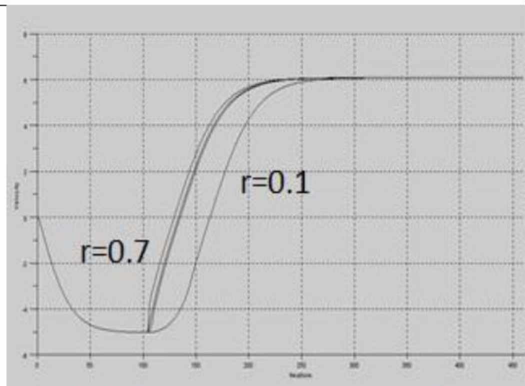

Fig. 3(b) Velocity of descent for various hole radii

C. Effect of Volume of un-deflated chamber (vol)

The effect of change in volume of un-deflated chamber on the time and velocity of descent for volume for a radius of hole of 30 cm is shown in Fig. 4(a) and (b), respectively. It can be seen that the altitude to which the aerostat rises due to free lift is increased as the volume of un-deflated chamber is increased, and then it starts sinking at a fixed rate. However, unlike the initial altitude of deployment and radius of hole the final velocity of descent is greatly affected by volume of un-deflated chamber; larger the volume of un-deflated chamber, lower is the terminal velocity.

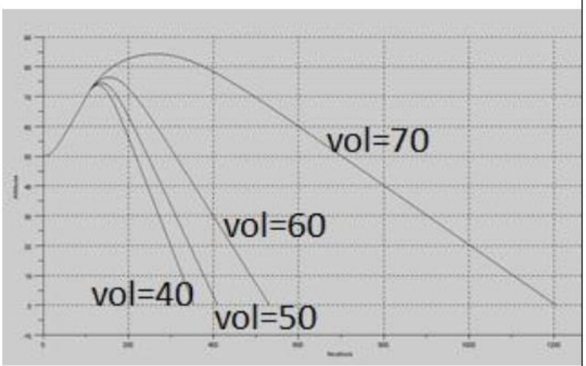

Fig. 4(a) Time of descent for various volume of un-deflated chambers

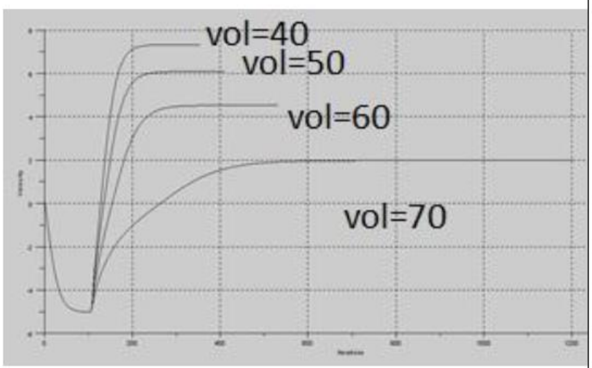

Fig. 4(b) Velocity of descent for various volume of un-deflated chamber

A study of breakaway characteristics of tethered aerostats has been reported by Dai et al [5]. The current model can be improved further by incorporating thermal characteristics as well as better stability and aerodynamic modelling schemes for the aerostat, which is currently under progress.

Conclusions

This paper describes a PRD mechanism and results of simulation of the trajectory and velocity of descent of the aerostat after the tether breaks. The various simplifying assumptions made in an existing simulation study have been removed to some extent. The results obtained from the enhanced simulation model indicate that the time of descent of the aerostat after the tether breakage is directly proportional to the initial altitude, volume of the un-deflated chamber and inversely proportional to the radius of the hole. However, the velocity of descent of the aerostat reaches its terminal velocity very soon and also varies inversely with the volume of the un-deflated chamber.

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