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Computational and Experimental Study for Reducing Forebody Wake Effect by Proper Designing of a Slit-cut Square Parachute used for Sonobuoy Drop

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ABSTRACT

This paper discusses the design of a square parachute based on classical approach, computational analysis and experimentation. This parachute will be used to drop directional sonobuoy on the sea to locate and classify the submarines. Design improvements are brought out by providing slits into a solid square canopy of parachute to bring in more stability and minimum drift during descend. Specifically, the effect of upstream sonobuoy, RANS model, suspension line length, canopy size and slit size in flow structure were considered. The predicted drag coefficients obtained from CFD for square canopy with slit-cuts compared with the results of wind tunnel experiment and found that the increase in the suspension-line length and/or of the surface area of the parachute canopy helps in better stability and results in the minimum drag loss.

Keywords: Drag coefficient; CFD; Sonobuoy; Square canopy parachute; Slit-cuts; Suspension lines; Forebody wake

NOMENCLATURE

ρ	Air density (=1.169 kg/m^3)
C_d	Drag coefficient
D_b	Maximum forebody diameter (m)
D_o	Parachute nominal diameter (m)
D_p	Inflated parachute diameter (m)
F_D	Drag force (N)
L	Suspension-lines length (m)
M	Mass of sonobuoy (kg)
q	Dynamic pressure at the canopy (N/m^2)
S	Canopy surface area (m^2)
V	Speed (m/s)
FSI	Fluid structural interface
IAS	Indicated air speed (m/s)
OPEN FOAM	Open source field operation and manipulation
RANS	Reynolds averaged Navier-stokes

1. INTRODUCTION

Sonobuoys are expendable electro-acoustic sensors which are air deployed from fixed and rotary wing aircraft[1] conducting anti-submarine warfare or underwater acoustic research. After launch, a parachute decelerator system stabilises and provide defined rate of descent to the sonobuoy prior to water impact. Precision aerial delivery is most important to drop sonobuoy to locate the submarines. In presence of forebody, performance of the parachute deviates from the expected behaviour in terms of loss in drag, stability and rate of descent. To prevent excessive shock to the sonobuoy on water entry, a decelerator or retardation device, usually a parachute, is deployed directly after launch as shown in Fig. 1. The parachute system slows the descent of the sonobuoy to an acceptable terminal speed and it also assures that sonobuoy impact on water at a small angle. The use of parachute has one deleterious effect on sonobuoy and allows the system to drift horizontally with wind during air descent. The magnitude of this drift is dependent upon the altitude of launch as well as the wind speed. Since profile of wind speed and direction varies with altitude is normally not known, the wind drift of the sonobuoy can be minimised by designing proper parachute shape.

Gupta[3] discussed the various types of parachute application for dropping of different payloads. Amongst these, guide-surface, cruciform or cross-type and square-canopy are

Figure 1. An aircraft dropping sonobuoy[2].

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main parachutes suitable for dropping the sonobuoy. The guide surface[4] parachute has good stability but complex in shape, geometry and inferior drag efficiency. Cruciform[5-6] or cross-type[7] parachute requires more suspension lines to maintain the shape and size, bringing in packing complexity and rotational possibility during operation. Besides, it adds more cost and chances of line entanglements. Warren[8], *et al.* has designed a square parachute made of woven Poly Hydroxyl Alkanoate (PHA) fabric material for 67 m/s terminal speed and 335 m altitude drop. But for high altitude and low terminal speed (7500 m, 30 m/s) as required under this study, drift and stability would be the major issue. Earlier, a study was carried out by Brian[9], *et al*. and Mazyar[10], *et al.* to view the effect of vent hole in a canopy on the performance of vented round-parachutes. They found that parachute was observed oscillating when Reynolds number exceeded certain values and also observed that every case has a stable and unstable region. Although there are many studies on measuring and predicting the aerodynamic parameters (e.g. drag coefficient)[11], there are few studies focused on the development of the wake flow past the canopy. But no literature could be found mentioning the effect of slits on a square parachute. To overcome all these problems, a novel design of square parachute with slit-cuts on its canopy considered for the analysis and used in dropping the sonobuoy. It is simple and the stability is improved by providing slits in the canopy and increasing the length of suspension lines (ref Fig. 2).

The current computational study carried out for steady state analyses of (i) parachute (ii) sonobuoy and (iii) of the combined system to determine the corresponding drag coefficients. The focus of the current work was to determine the effect of sonobuoy on parachute performance in terms of suspension lines length, drag coefficient and parachute behaviour that produce flow features in the wake that matched best to the experiment.

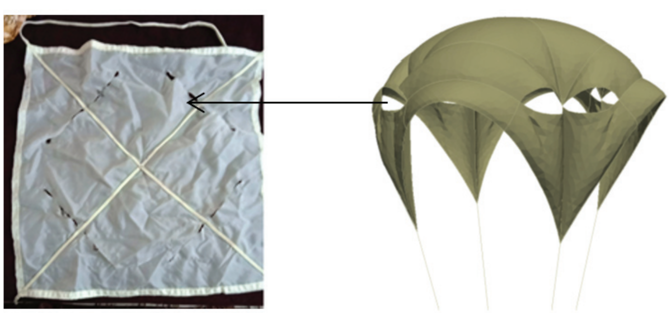

Figure 2. Flat surface square parachute with slits and its inflated shape.

2. DESIGN APPROACH

The objective of this parachute is to drop the sonobuoy from 7500 m altitude, Above Mean Sea Level (AMSL) from 190 m/s to 30 m/s at touchdown. It is to be used in marine environment where winds are very high and requires precision drop. Parachute designed based on air descent, altitude, decelerator size, and weight. The brief design inputs are:

- Mass : 9 kg
- Maximum altitude : 7500 m AMSL
- Maximum launch speed : 190 m/s IAS
- Terminal speed : 30 m/s

The air density (ρ), temperature (*T*) and pressure (*P*) at sea level are the usual reference values. The atmospheric condition taken from Indian standard is as:

Temperature : 300.7 K
Pressure : 100900 Pa
Density : 1.169 kg/m^3

The design variables to be determined from the analysis are:

(i) Size of the parachute,
(ii) Suspension lines length, and
(iii) Drag coefficient.

2.1 Canopy Sizing

The objective of design is to keep the opening shock and drift minimum. In view, a square canopy with slit-cuts was selected to provide the minimum opening shock, better stability and minimum drift. The vertical descent of the sonobuoy is determined by the gravity and fluid drag forces acting upon it. Once the parachute is fully deployed and increased drag causes the sonobuoy descent to slow, at equilibrium, the gravitational and drag forces are balanced and given by Eqn (1).

$$Mg = (½)\, \rho\, V^2 [C_d (\pi/4)\, D_o^{\,2}] \tag{1}$$

The drag coefficient (C_d) is widely used as a measure of parachute performance. It is defined as given in Eqn (2).

$$C_d = \frac{F_D}{q \cdot S} \tag{2}$$

The nominal C_d of flat square canopy parachute ranges from 0.60 to 0.65[12] (without slits). A value of 0.6 was taken for estimating the size of the canopy, while the maximum C_d value of 0.65 was chosen for parachute peak load calculation. Neglecting the drag force on sonobuoy, the following equilibrium can be used in balancing the forces during terminal descend, using Eqn (1).

$$9 \times 9.81 = 0.5 \times 1.169 \times 30^2 \times [0.6 \times (\pi/4)\, D_o^{\,2}]$$

$$D_o = 0.6 \text{ m}$$

Therefore, the size of each side of square canopy = $[\pi/4 * 0.6^2]^{0.5}$ = 0.50 m.

Knacke[13] suggest that for comparable size of the forebody, the drag area of the parachute could reduce from 10 to 20 % due to decreased dynamic pressure in the wake region. Hoerner[14] estimated the effects on drag force when placing a payload on a canopy and found that the wake created by the payload reduces the drag coefficient of the canopy by approximately 22 %, assuming that the diameter of the payload was 1/3rd the size of the canopy itself. This calculation however does not take into account the mass of the payload nor the length of the suspension lines. According to Knacke[13], drag coefficient reduces because of the forebody wake and can be made to increase by increasing the length (*L*) of suspension-lines such that L/D_o is more than one. Therefore, for the current study, with most conservative approach, the ratio of suspension-lines length to parachute diameter was taken as one, so

Length of suspension lines, $L = 1*0.60 = 0.60$ m.

3. GEOMETRY AND COMPUTATIONAL ANALYSIS

The flow past an aerodynamic parachute with a vent hole was examined by Cao & Jiang[15] experimentally and numerically and found that discrepancies between the actual and the expected results from the analysis may be due to flow entering the canopy. The drag coefficient of a parachute in steady as well as in turbulent conditions for various Reynolds numbers was evaluated through CFD[16]. Accorsi[17] *et al*. have carried out a comprehensive computational analysis for three-dimensional simulations of round parachute fluid-structure interactions and this technique is applied to simulate the airdrop performance and control phenomena in terminal descent and used steady-state RANS solver in Open FOAM (simple Foam) in 3D parachute inflation. There are multiple literatures[18-19] available on Open FOAM (simple FOAM) validation in the open domain and can be referred easily. The Ph.D. thesis of Jasak[20] also provides a detailed description of the algorithm as used in Open FOAM. The software chosen for this parachute analysis is also Open FOAM because it is user-friendly and jointly customised by Zeus Numerix-ADRDE (ParaZ). It is a FSI simulation solver for large deformation and flexible structure. This module carries out the fluid flow physics and solves the governing equations using RANS model. Therefore, computational analysis was carried out to determine the right size of the slits provided on the canopy, with the number of rigging line taken as four because of four corners of the square canopy. The outcome of the CFD analysis provided the size of each slit as 90 mm, as shown in schematic diagram at Fig. 3.

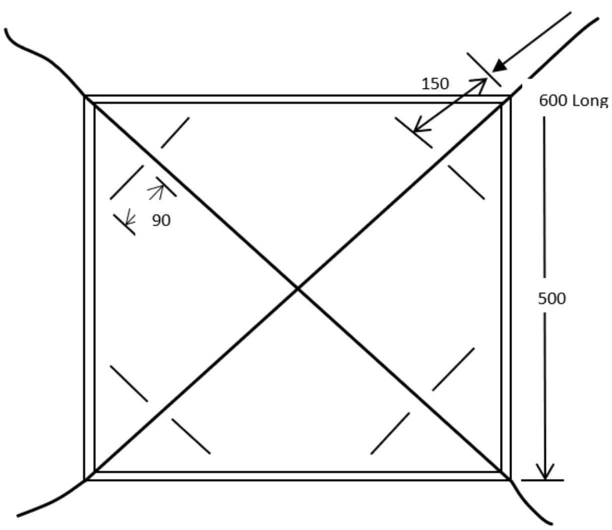

Figure 3. Geometry of Square canopy with 8 slit-cuts, 90 mm equal spaced 150 mm apart from skirt (all dimensions are in mm).

The analysis was carried out in a steady CFD-structural coupling iteration, where at the end of each CFD convergence, the pressure data were mapped on the canopy and a new canopy shape is obtained by structural iteration. The process repeated till a steady shape of the canopy was obtained. A 3D RANS equations and simple pressure velocity coupling, k-ε turbulence model used for CFD analyses. The thickness of the parachute fabric was taken as 0.5 mm, tapes (16 mm width) and suspension lines (16 mm tapes) all were considered as nylon fabric properties (2.7 GPa) for structural analysis. The surface was triangulated. Since flow velocity as being low (30 m/s), a pressure based solver and upwind convection scheme was used. Zero gauge pressure was considered at the outlet boundary condition. The computational mesh for the simulation was created using the Open FOAM block Mesh utility. Total surface mesh created was 13000 and approximately one million tetrahedral elements were generated for a coarse mesh after executing several iterations of FSI. The computational domain and boundary conditions are given in Table 1 and Fig. 4.

Table 1. Simulation flow parameters

Parameter	Value
Fluid	Air
Inflow	Constant velocity of 30 m/s
Outflow	Static pressure
Side boundaries	Symmetry planes
Inflow location	3.5 m upstream
Outflow location	10.5 m downstream

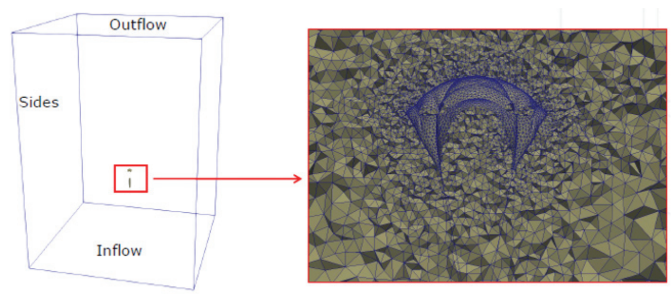

Figure 4. Parachute FSI: CFD domain.

The body is kept stationary in the flow stream. There were no gravity or buoyancy effects considered during the analysis. The different cases were examined corresponding to a terminal velocity 30 m/s.

The outcome of the CFD analysis in terms of contour-plot of velocity (left side) and pressure (right side) for parachute, sonobuoy and combined system are plotted as shown in Fig. 5.

The maximum pressure in the inflated canopy without sonobuoy was found to be 568.01 Pa, and drag coefficient as 0.58. In presence of sonobuoy, the total pressure of the flow-field faced by the parachute was reduced to 300 Pa and overall drag coefficient of 0.428. Further analysis was carried out with increase in the suspension-lines length to reduce the wake effect to compensate the loss in drag force.

3.1 Increase in Suspension Line Lengths

Deploying a small parachute in the wake of a forebody causes considerable loss in drag and affects the stability of the parachute. According to the test conducted in NASA and Wright Field Vertical Wind Tunnels[21] for vertical descending bodies, the parachute should be ejected from a distance more than four times (preferably six times) the forebody diameter into good airflow behind the forebody. Apollo and other

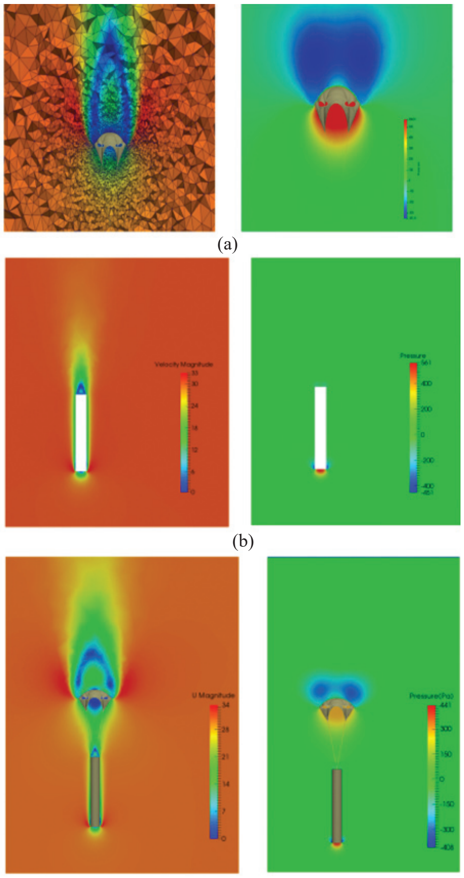

Figure 5. Velocity and pressure profile of (a) parachute, (b) sonobuoy, and (c) combined system.

NASA programs[22] had used six times forebody diameter rule successfully. But no literature could be found mentioning the effect of suspension line on slit-cut square parachute for dropping a small cylindrical sonobuoy. Therefore, CFD analysis was performed at different suspension-line length and the velocity contour-plot was obtained. It is found that the forebody wake influence reduces as distance increases from the edge of the forebody as shown in Fig. 6.

The four different suspension-line lengths were examined in CFD and corresponding drag coefficients are reported in Table 2. It is seen that as the forebody moves away from the parachute canopy, the overall coefficient of drag, C_d, improves.

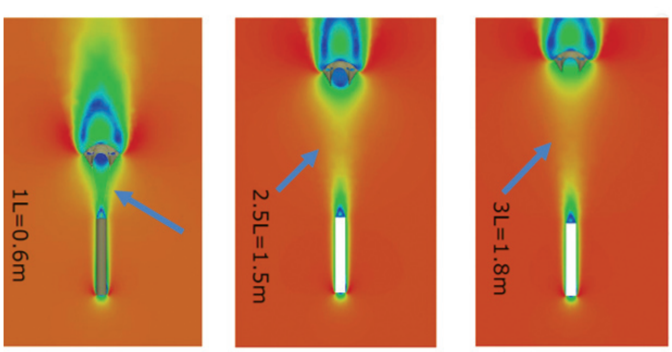

Figure 6. Effect of suspension line length (velocity contour).

Table 2. Effect of variation in suspension-line length

Suspension-line length to forebody diameter (L/D_b)	Overall drag coefficient (C_d)	% drag loss caused by forebody wake
5	0.428	28.67
7.5	0.430	28.33
10	0.520	13.33
12.5	0.623	No wake effect

Keeping in view of previous studies and literatures, in this study, the ratio of suspension lines to forebody diameter (L/D_b) is also chosen as 5 D_b (0.60 m). Therefore, the higher size of canopy is required to be chosen to compensate the drag loss (Table 2).

3.2 Enhanced Surface Area of Parachute

Keeping in view of drag loss and desired terminal velocity, an enhanced area of the canopy is to be evaluated.

Enhanced area = (Original area) x (Desired drag coefficient/Actual drag coefficient)

= (0.50 x 0.50) x (0.60/0.428)

= 0.35 m^2

Equivalent diameter of the canopy (D_o) = 0.67 m

Side length of square canopy = 0.60 m

So, new enhanced area of canopy = 0.60 x 0.60

= 0.36 m^2

Based on new dimension of the parachute, the geometric has been are re-modelled and CFD analysis was carried out. The overall drag coefficient of the parachute-payload system is now increased to 0.44. The same configuration of parachutes was tested in wind tunnel which is to be discussed in next section.

4. WIND TUNNEL TESTING

Carlie[23] *et al*. conducted wind tunnel tests at subsonic speeds to evaluate decelerator characteristics as a function of suspension lines length. Underwood[24] *et al*. conducted the various types of parachutes in subsonic wind tunnel and estimated the effect of wake on the parachute performance. In this study also, using the same configuration of parachute, wind tunnel tests were conducted at subsonic speeds to estimate the variation in drag coefficient in presence of sonobuoy. A full scale model of the sonobuoy, parachute and combined system were fixed to the bottom of test section by a strut parallel to the direction of flow**.** The wind tunnel test section size was 3 m wide 2.25 m high and 8.75 m long. The wind tunnel experimental setup consists of the sonobuoy mounted on an instrumented vertical rigid sting as shown in Fig. 7. The vertical sting is mounted on the central disk of the test section floor instrumented with a six-component strain gauge balance.

A load cell is used in the model to measure parachute loading. The dimensional details of the parachute and sonobuoy are given in Table 3.

Table 3. Details of parachute and sonobuoy model

Model details	Diameter (m)	Reference area (m^2)
Parachute (L/D_b = 5)	0.670	0.360
Sonobuoy (Length = 0.914 m)	0.122	0.012

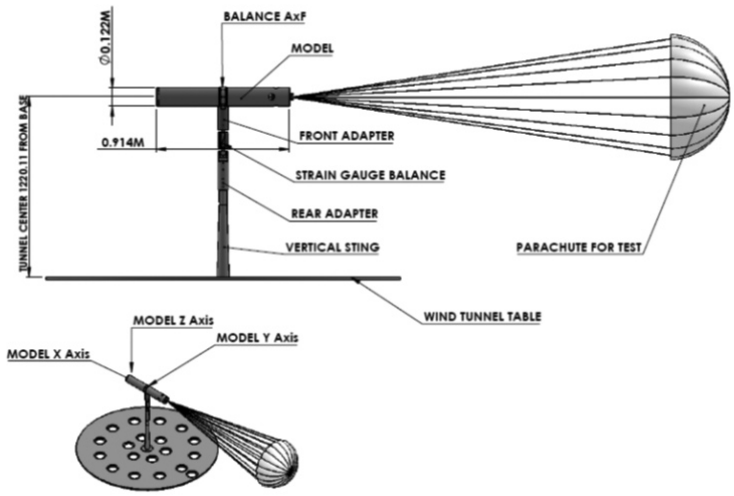

Figure 7. Experimental setups for sonobuoy drag measurement with parachute.

The parachutes tested had canopies made of nylon material predominantly 75 gsm, 805 N/5 cm strength. The parachute was packed in a deployment container and a lines first deployment method was used. To achieve higher effective drag area ($C_d S$) the number of suspension lines kept four and evaluated. The total quantity of runs made in the wind tunnel was approximately 33 including a combination of decelerator lengths and canopy area. The recorded opening drag coefficient data of parachute with slits, sonobuoy body and combined system are illustrated through Figs. 8 to 10 respectively.

(i) Parachute with slits

The parachute with slits was tested in wind tunnel to capture the drag characteristics in deployment mode at 30 m/s to 40 m/s wind velocity. The drag coefficients of the parachutes calculated from the measured drag force and found in range of 0.43 to 0.46 as illustrated in Fig. 8.

(ii) Sonobuoy

Tests were also conducted on sonobuoy body in wind velocity step mode from 20 m/s to 40 m/s to measure its drag at wind incidence angle of 0º, 15º, 30º, and 45º. At 0º wind incidence angle, the drag coefficient of the sonobuoy was found in the range of 1.20 to 1.26 as illustrated in Fig. 9. It is seen that the drag coefficient was found to be constant after 30 m/s.

(iii) Combined system

Further, the sonobuoy-parachute system was tested in wind tunnel in velocity step mode at 20 m/s to 40 m/s. The drag coefficient of the system was found as 0.43 to 0.53 as illustrated in Fig. 10. During wind tunnel testing, the parachute models were found stable but little oscillation observed.

5. RESULTS AND DISCUSSION

The CFD analysis carried out in clean stream air flow and wind tunnel tests were performed with certain limitations. However, the results are comparable. The drag coefficients of the parachute, sonobuoy body and combined system obtained from the CFD and wind tunnel tests are summarised in Table 4.

The parachute behaviour found in CFD and wind tunnel tests were stable except minor oscillation in parachute. It is

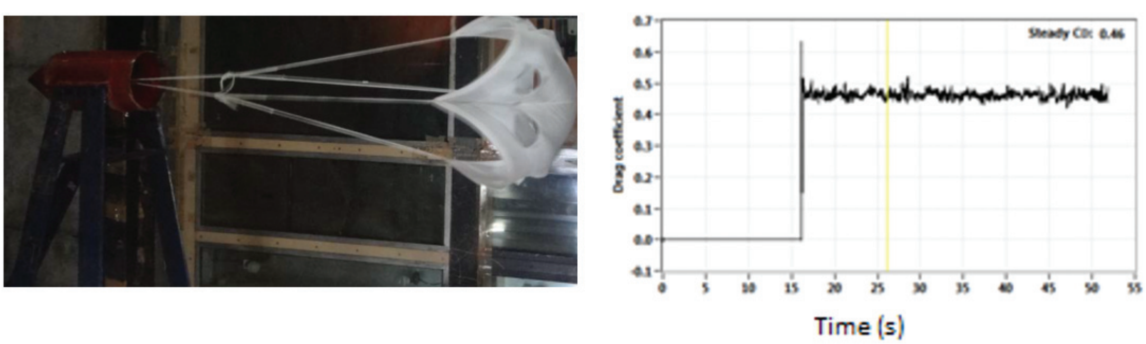

Figure 8. Test result for deployment and drag characteristics of parachute model tested at 30.1 m/s wind velocity.

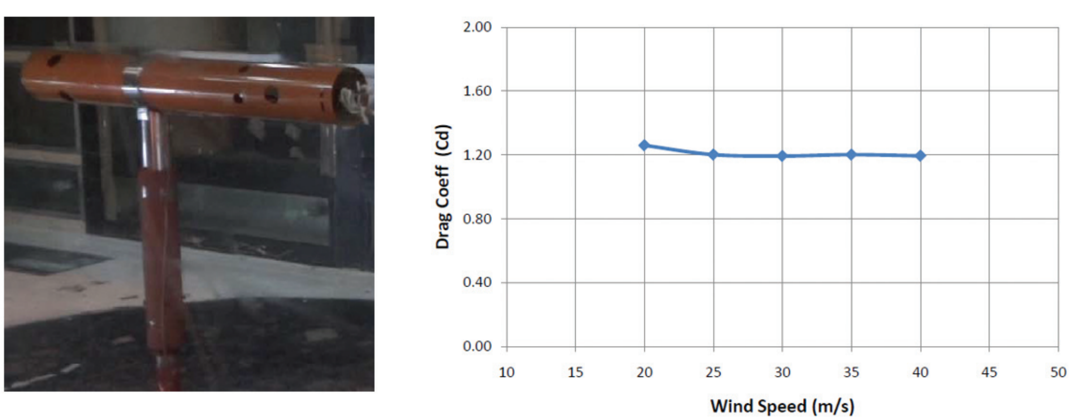

Figure 9. Drag characteristics of Sonobuoy tested alone at Beta = 0º in wind velocity step mode.

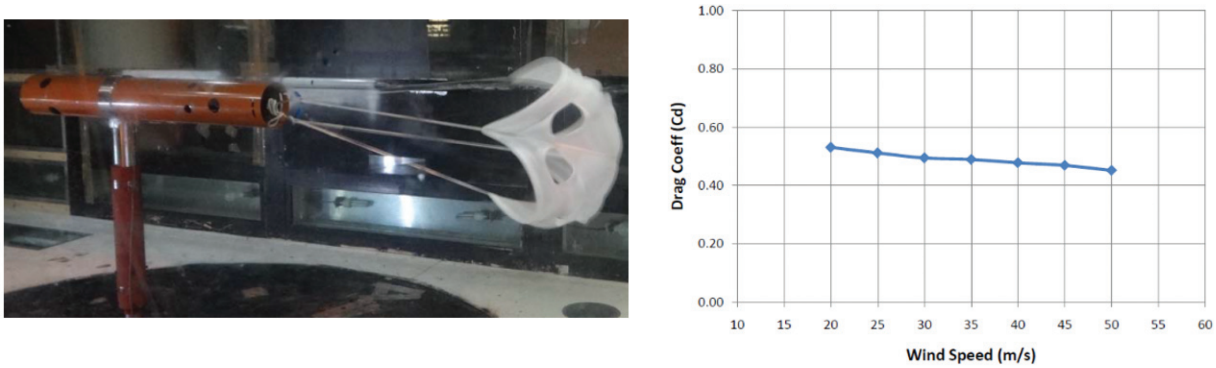

Figure 10. Drag characteristics of parachute model tested with sonobuoy in wind velocity step mode.

Table 4. Coefficient of drag of parachute, sonobuoy, and combined system

Test article	Drag coefficient		Remark
	CFD (wind velocity 30 m/s)	Wind tunnel (wind velocity 20 m/s to 40 m/s)	
Parachute	0.58	0.43-0.46	C_d (Wind tunnel) < C_d (CFD) due to packing container present in the stream line in wind tunnel test.
Sonobuoy body	1.2	1.2-1.26	
Combined system	0.428 - 0.44	0.43 - 0.53	

due to slit based construction of canopy but overall system performance was acceptable. The trapped air inside the canopy goes out easily from all the quadrants of the canopy through slits.

6. CONCLUSIONS

Design improvement of the parachute was carried out for dropping of a high altitude sonobuoy to reduce the velocity from 190 m/s to 30 m/s. Literatures provide the drag coefficient for the solid canopy but no works so far investigated on square canopy with slits. Therefore, this study was undertaken to investigate the effects of suspension lines length, canopy surface area and drag coefficient of slit-cut parachute. After working out the dimensions of the solid canopy, and the right fabric for the canopy, suspension lines and the radial tapes, computational fluid dynamic analyses carried out to determine the right size of the slits and suspension line lengths. The drag coefficient was computed through CFD by simulating the steady airflow and the results were compared with the experimental tests obtained from wind tunnel. CFD analysis was performed at different suspension-line lengths and found that the forebody wake influence reduces as suspension lines length increases from the edge of the forebody. Maintaining the L/D_b as five (as suggested in literature), drag coefficient was improved by 2.8 % by enhancing canopy surface area by 44 %. There were 12 tests on slit-parachute with packing container, 28 tests on parachute with sonobuoy and 20 tests on sonobuoy body conducted in wind tunnel at a speed of 20 m/s to 40 m/s. Table 4 shows a comparison of the C_d computed based on air descent rate (30 m/s) and the C_d measured in the wind tunnel for the same configuration. The overall drag coefficient of the combined system is matching in case of computational and experimentation method. Based on the present research work, it is suggested that, while providing slits on the parachute, the wake distance should simply be 5 times of forebody diameter (D_b) with enhanced canopy area to get the maximum drag force.

However, further work can be extended with different slit configurations and sizes on canopy with other type of parachutes. Further, consideration of a staging of parachute, a concept of free fall sonobuoy and then opening of parachute can be studied to improve the decelerator aerodynamic characteristics.

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CONTRIBUTORS

Mr Mahendra Pratap is working as Scientist ‘F’ at Aerial Delivery Research & Development, Agra. He has headed various projects in the field of parachutes and currently engaged as Project Director of Aircrew Smart Ejection Seat. His areas of interest are: Design of various parachutes, reliability and quality assurance, testing and evaluations. He is a life member of INSARM and Ae.S.I. He has been awarded Lab young scientist and Group Technology awards.
Contribution in the current study, he has contributed in design and development of parachute system for sonobuoy, testing and evaluation of parachute, modifications, dynamic and flight tests.

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Contribution in the current study, he has extended supervision to the main author for the analysis, outline of the research work, analysis of the CFD results, design parameters, literature survey and final scrutiny of the paper.

Dr Subhash Chandra Sati is presently honoured with DRDO chair at R&D Engrs Pune. Earlier, he had served as a Director, ADRDE; Director General (NS & M), DRDO. He was awarded PhD from Pune University, India. His areas of interest are: design, analysis, simulation and realisation of electro hydraulic control system; bond graph based modelling, simulation and analysis for physical system dynamics, multidisciplinary system engineering and product realisation. He received various awards, Path breaking research & technology, VM Ghatage, Agni award scientist of the year award (2009) and other DRDO Awards.

Contribution in the current study, he has guided the main author for design and interpretation of results, finalising the configuration, encouraged paper writing and review of this paper.

Mr A.K. Saxena is Outstanding Scientist and Director of ADRDE Agra, DRDO, India. He has been awarded various DRDO awards like "Agni award for self-realisation" and Lab Group Technology award. His main area of works is the design of personnel parachutes, Winch & Mooring System of Aerostat and realisation of Heavy Drop System for various transport aircrafts.

Contribution in the current study, extended support in slit design analysis, validation, testing, literature survey and improvement of this paper.