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Forebody Wake Effects on Parachute Performance for Re-entry Space Application

Mahendra Pratap[@,*], Anil K. Agrawal[#], Subhash C. Sati[@], and Vipin Kumar[@]

[@]*DRDO-Aerial Delivery Research & Development Establishment, Agra - 282 001, India*

[#]*Department of Mechanical Engineering, Indian Institute of Technology-BHU, Varanasi - 221 005, India*

[*]*E-mail: mahendra.pratap@adrde.drdo.in*

ABSTRACT

Forebody generates its own wake that influences the performance of aerodynamic decelerators during the flights. Many parachute Jumpers have experienced the failure of an ejected pilot chute as the parachute canopy collapsed and fell back on the Jumper because of wake developed behind the Jumper. In the available literature, limited data is available to predict the exact loss of parachute drag in presence of the forebody (FB). The purpose of this paper is to generate a comprehensive aerodynamic data to study the behaviour of FB-parachute dynamics by conducting the wind tunnel experiments. Wind tunnel test has been carried out to establish the initial design parameters of aerodynamic parachute. The experiment was carried out on a scale down model of 20 degree conical ribbon drogue parachute and FB with and without each of them at a subsonic speed for studying dynamic stability characteristic for different orientation of FB. The test results indicate that to ensure adequate stability for the capsule to descend vertically at a low subsonic speed, a cluster of two drogue parachutes be used. Under such condition, the overall drag coefficient found to be above 0.50 providing not only a safe descends velocity but increasing reliability of mission as well.

Keywords: Wind tunnel test; Coefficient of drag; Aerodynamic interface data; Forebody; Parachute; Wake effect

NOMENCLATURE

β	Side slip angles (in degree)
CP	Cluster of two parachutes
D_p	Inflated parachute diameter (m)
D_0	Nominal diameter of parachute (m)
D	Maximum diameter of forebody model (m)
F_d	Peak force (N)
F_{sd}	Steady drag force (N)
F_x	Applied force (N)
V_x	Sensor output (mv/V)
V_0	No load voltage output from the sensor (V)
S	Slope of the calibration curve (degree)
L	Total of length of suspension line and of riser (m)
L_e	Suspension lines length (m)
R	Riser length (m)
SP	Single parachute
USAF	United State Air Force

1. INTRODUCTION

The parachute is always used with forebody as an aerodynamic decelerator to provide retardation and stability to a payload[1]. The parachute aerodynamic characteristics is significantly, affected by the presence of the forebody (FB). The FB causes unsteady pressure forces and reduced streamline velocity relative to the free stream airflow resulting wake on the aft body that is the primary source of dynamic instability and may result into failure of operation. The turbulent wake generated by the FB flows into the parachute and causes reduction in parachute drag and thus stability. The distance between the leading edge of the parachute and the rear of the FB was kept to a minimum to save weight[2].

At subsonic speeds, there is a large pressure differential at the parachute skirt band (positive outward) that causes full inflation of the parachute. At the supersonic speeds, the shock waves extend from the front of the canopy across the skirt plane and beyond the canopy. Parachute drag loss due to FB wake is usually greater at supersonic speeds than at subsonic speeds, because the momentum effect of the supersonic wake is usually significant larger than the momentum effect of the subsonic wake and also due to higher dynamic pressure associated with supersonic flight. A comprehensive discussion on the effect of FB-induced wakes due to parachute drag at subsonic, transonic and supersonic speeds is given in the USAF parachute design manual[3].

The phenomenon of parachute FB dynamic stability is one of the least understood aspects of the atmospheric entry, decent, and landing and it is a big challenge to the space mission program. Analytical and computational techniques used to predict the dynamic response of the missions are inadequate. Then, the scientists are still relying on experimental methods to estimate the expected aerodynamic stability data. Literature available[4,5] in the field of drogue parachute drag presents the data from many flight tests that are for their specific configuration of FB. The forebody considered in the mission under study is a different one and thus the available

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data needs to be examined. Because of this issue, the present study undertaken even designing of the parachute and the effect of FB wake is considered while evaluating the parachute performance. The study on the Orion pilot chute[6] also observed that the variation in drag of pilot chute is mainly due to FB. In that study, a three degree of freedom mathematical analysis was carried out on parachute-payload for a variety of vehicle dynamic conditions and parachute configurations to enables the designer to predict the undesirable recovery attitudes. Literature study[7] showed that deploying a parachute opposite to oscillating motion of the FB may increase the parachute opening force by as much as 20 % and drag area of the parachute could reduce as much as 10 % to 20 % due to decreased dynamic pressure in the wake region. In an another work[8], an investigation on flight dynamics of a parachute payload system has also been carried out. A generalised pressure recovery fractions wake model was developed for Orion parachute assembly[9] using computational fluid dynamics and this model is still being used in designing of the pilot parachute. This study is not useful for drogue parachute consider in this paper.

Guglieri[10], has carried out a study on a cluster of two parachutes by varying their size independently of the other. The experimental results were different from the results of the numerical analysis of parachute payload system. Further, the variation in riser length was not part of the study.

In the present work, the shape of FB (Crew Module) is taken to be truncated cone with spherical nose cap to minimize re-entry heating. The present work proposed to use a cluster of two drogue parachutes. The two drogue parachutes were designed considering design factor 1.9 to 2 of the drogue parachute components[11] for the recovery of experimental space payload of 3.5 ton. The drogue parachute must facilitate the speed for opening of the main parachute[12] that is to be obtained while recovery of payload initiated at designated altitude and velocity. At this speed, the payload requires the drogue parachute for first stage retardation and to stabilise itself. For this purpose, wind tunnel experiment was carried out to generate aerodynamic data on the parachute oscillation behaviour, wake effect, stability and various aerodynamic forces. A model was used in the experimentation which was a scale-down version of actual prototype with the dimensions given in Table 1.

The experiment was carried out to determine the drag coefficient with payload oscillatory in the range of ±15° for the following causes:

(a) Forebody alone
(b) Single parachute alone
(c) Cluster of two parachutes alone
(d) FB with single parachute
(e) FB with cluster of two parachutes.

Table 1. Full scale parameters of forebody and drogue parachute

Forebody		Drogue parachute (Conical ribbon)	
Parameter	Size and shape	Parameter	Size
Maximum diameter (D)	3.1 m	Nominal diameter (D_o)	6.27 m
Depth	2.685 m	Canopy surface area (S_o)	30.88 m^2
Shape	Truncated cone with spherical nose cap	L_e/D_o	1.2
		Riser plus suspension line length (L)	15.50 m

Drag coefficient computed from the using a six-component strain gauge balance attached over a vertical boom and with the help of a load cell as shown in Fig. 1.

Since the drag coefficient value is almost constant in subsonic region, speeds selected for the tests were 20 m/s, 30 m/s, 40 m/s and 50 m/s. Keeping in view, the wind tunnel cross section and the blockage effects, the size of the model was decided so as to yield the equivalent Reynolds number to actual full scale test or operational conditions as what will be experienced in actual condition. This requires a scaling factor of 6.43:1 for the tunnel test section of the size 2.25 m x 3 m x 8.75 m.

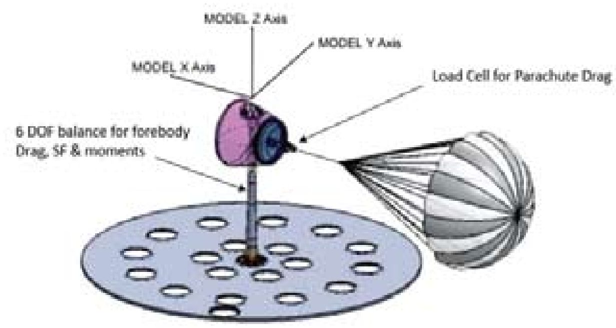


Figure 1. Mounting scheme of FB and parachute model.

2. MODEL DESIGN AND FABRICATION

To determine the effectiveness of drogue parachutes in stabilising a 3.5-ton experimental capsule, an experimental investigation has been carried out with FB and parachute scale down to the same ratio.

2.1 Forebody

The model of FB is fabricated using fiber reinforced plastic material. The scaled model dimensions are given in Table 2.

Table 2. FB model dimensions

Item	Parameters	Values
FB model	Reference area	0.185 m^2
	Maximum diameter (D)	0.485 m
	Length (along axis)	0.417 m

2.1.1 Inspection of FB Model

Profile inspection of FB model is carried out at selected locations in 20 steps. To do accurate profile inspection, scaled CAD model is divided into number of smaller sections having 30 mm distance starting from the base of the model. After selecting the positions, diameter (design diameter) at respective locations are noted down. Now, these locations are transferred to the fabricated model using height gauge placed on a surface table. The profile measurement in terms of the diameter (measured diameter) is carried out using outside caliper and is measured using Vernier caliper. The difference between the two diameters is divided by 2 to get offset value from the profile. The detailed summary of the profile is presented in Table 3.

Table 3. Forebody model profile accuracy measurement

Design diameter (mm)	Measured diameter (mm)	Offset from profile
299.9 mm	299.3	0.3
327.5086	326.5	0.5043
339.1453	338.5	0.32265
349.1536	348.9	0.1268
359.1288	358.5	0.3144
369.1039	368.5	0.30195
379.0790	378.5	0.2895
389.0541	388.5	0.27705
399.0541	399	0.02705
409.0043	409	0.00215
418.9794	419	-0.0103
428.9545	429.5	-0.27275
438.9297	439	-0.03515
448.9048	449.5	-0.2976
458.8799	459	-0.06005

2.2 Parachute Model

Parachute model utilised for wind tunnel test is as similar as in geometry and also with flexibility as of the full-scale parachute. The detailed scaling method, model design and testing in wind tunnel of parachute has been discussed by Kumar[13]. A study was carried out on a 20-degree conical ribbon parachute model in wind tunnel[14] having 1 m diameter, 24 gores, geometrical porosities from 15 % to 30 % as in the prototype parachute, and suspension line lengths 1-2 times the parachute's nominal diameter without the FB and established the effects of these parameters on parachute performance.

The parachute models were fabricated with sample margins to avoid wear points such that the model parts could be refurbished, for example, by making the suspension lines replaceable. A simplified construction technique was used for the model parachutes to avoid it to be come over stiff due to reproduction of all the seams and joints. High parachute stiffness impacts opening behaviour of the parachute and results in less drag. Fabric permeability issue has been handled by preparing the model of the same fabric material. The detail of the parachute model is given in Table 4. The configuration of the parachute will be changing only in riser length.

2.3 Instrumentation and Data Acquisition System

The force measurement system consists of a window-based host computer installed with LabVIEW application software. Signal from six-component strain-gauge balance and a single component load cell are acquired using a high-accuracy 18-bit data acquisition PXI-6289 module of the PXI system through a Universal strain-gauge signal conditioner SCXI system.

Table 4. Dimensions of the parachute model

Parameters	Values
Shape nominal diameter (D_0)	20-degree conical ribbon parachute 0.664 m
Nominal area	0.3463 m^2
Number of gores	24
L_e/D_0	1.2
Riser and suspension line lengths riser length	5 D, 7 D, 10 D 1.62 m, 2.825 m, 4.03 m

2.3.1 Load Cell Calibration

The accuracy of the force measurement system using load cell is maintained within ± 0.5 % of the full-scale range through periodic calibration of the load cell. A calibration file is created by applying multiple known loads to the load cell and acquiring its voltage signal. The load cell calibration coefficients are calculated using this calibration data file. It is observed that the load cell response is linear and only linear slope is enough to determine the corresponding load. The drag force applied by the parachute under the test is calculated by the data acquisition software using Eqn. (1) given below.

$$F_x = S\,(V_x - V_0) \tag{1}$$

2.3.2 Six-component Strain-gauge Balance Calibration

Calibration of the balance is done for the accurate measurement of forces acting on the model during the test. Calibration procedure uses a single component calibration rig. Pre-calibrated dead weights are used for loading using gravity-loading methodology. Levelling of the balance is performed at each loading point. Entire calibration procedure including initialisation, bridge nulling, data acquisition, monitoring of the acquired test data, computing the inverse matrix and the final acceptance check of the balance are performed by LabVIEW. The calibration process consists of creating a calibration data file by applying a series of known loads to the balance and acquiring its electrical signal output. The balance calibration matrix is determined using this calibration data file. The inverse of calibration matrix, also known as load matrix, is used for computing the aerodynamic forces and moments.

3. WIND TUNNEL TEST SETUP

Earlier works, either theoretical or experimental, are not applicable for the application envisaged in the present work. Macha[15] provides wind tunnel study data for bluff-shape parachute. The work carried out by Poddar[16] is explicitly explained the wind tunnel model test on a circular-slotted, conical ribbon and ring slot parachutes without any FB. The work carried out by Kumar[17], *et al.* is for hybrid parachute (nylon-Kevlar) without payload and validated the same through dynamic tests. These studies do not reflect the performance of a parachute in presence of wake effect in presence of forebody as considered in this study. Hence, the present work includes wind tunnel testing on a parachute with and without payload.

The aerodynamic characteristics of the parachute-FB system depend on inflated-parachute diameter (D_p), FB diameter (D), parachute geometry and distance from the end of the FB to the leading edge of the inflated parachute canopy (wake distance).

3.1 Experimental Setup

The experimental setup under investigation used for measurement of drag force for a single and cluster of two parachutes with and without FB model are shown in Fig. 2.

The FB is mounted on a stand in place of canister as shown in Fig. 2(a). Pre-calibrated six component strain-gauge balance and a load cell are mounted on a vertical sting installed on the central disc of a turn table mounted on the test section floor (refer Fig. 1). The required side slip angle (β) of FB model from 0° to ±15° during model testing is achieved using turntable motion control system.

First, wind tunnel test on FB model alone is conducted for side slip angles of 0°, ±5°, ±10°, and ±15° at wind velocity from 20 m/s to 50 m/s. Test results in terms of drag force confirmed the model symmetry. The test data repeatability is established by performing repeat test runs.

The drag force measurement of parachute behind the FB model is carried out using strain gauge balance as well as a 150 kg range load cell at speed from 30 m/s to 50 m/s. A single or a cluster of two parachutes is attached to the load cell shown in Figs. 2(b) and 2(c).

4. TEST RESULT AND DISCUSSIONS

The results of the test on FB alone, parachute alone and of combined system are described in the following sub-sections.

4.1 Effect of Forebody

The coefficient of drag (C_d) of FB measured in sweep mode test, velocity ranging from 20 m/s - 50 m/s at different beta angle (β) and the result obtained are listed in Table 5.

The results, presented in Table 5, clearly show that with β being high, C_d either increased or stays constant. Further, the percentage change in C_d value is not very high. An optimum value of C_d is desirable, particularly when FB is to fall freely without drogue parachute. However, in real application, beta is not under the operational control. Being conservative, particularly for space mission, C_d value is taken to be the lowest one as 0.97.

4.2 Effect of Parachute

Drag force on a single conical ribbon parachute was measured multiple times at each of the speeds 30 m/s, 40 m/s, and 50 m/s. The mean value of drag force, drag coefficient, and shock factor found in this experimental investigation are presented in Table 6.

Table 5. Results on FB alone (wind speed 20 m/s to 50 m/s under sweep mode)

Beta angle (β)	C_d
0	0.98
5	0.99-1.0
-5	0.98
10	1-1.01
-10	0.98-0.97
15	1.01
-15	0.98-0.97

The drag coefficient of single parachute with respect to the time is shown in Fig. 3 and is found to be 0.54 in the steady state condition. The effect of variation of riser lengths on the drag coefficient is also plotted and shown in Fig. 4.

During the wind tunnel test the parachute was found to be stable with no rotation and revolution. The value of coefficient of drag (C_d) is the range of (0.50, 0.55) is safe. A higher value of parachute C_d is desirable, but prohibitive in space mission if it asks for carrying more of weight. Since the rise in riser-length will cause increase in weight, a lower riser-length would be preferred. Since riser-length as 5D is providing C_d in the range of (0.54, 0.55) for the operating velocity range from 30 m/s to 50 m/s and therefore, better to use parachute drag coefficient in the range of (0.50, 0.55) and riser length value equal to 5D is good enough.

With this in view, the experimentation in the present work has been carried out for the riser at greater than or equal

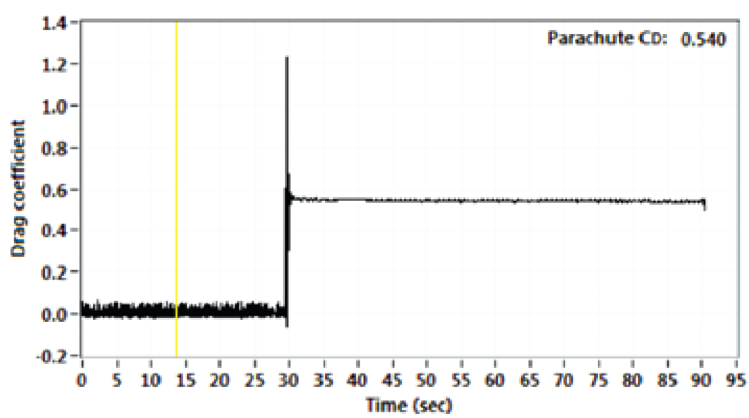
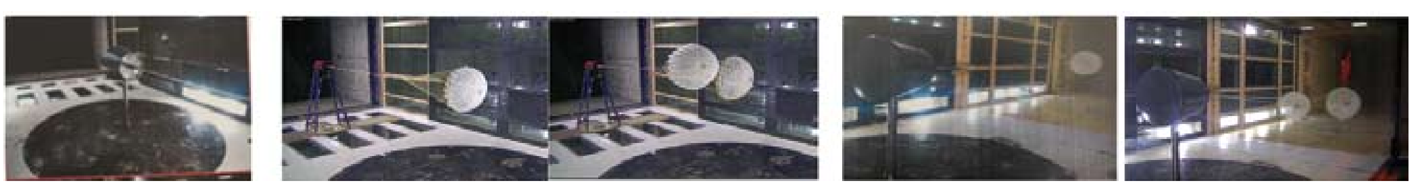


Figure 3. Parachute coefficient of drag (SP_R1) in deployment mode at 40 m/s.



(a) (b) (c)

Figure 2. Wind tunnel test setup (a) Forebody alone (b) single and cluster of two parachutes without FB (c) single and cluster of two parachute with FB.

Table 6. Wind tunnel test results for single parachute model without FB

Riser length (R), m	Speed (m/s)	Drag force (N)	Mean (C_d)	Remarks
1.26	40	Steady drag =176	0.54	Deployment mode Peak = 401.60 N Shock factor = 2.28
1.26	30	100	0.54	Sweep mode test
	40	180	0.55	”
	50	283	0.54	”
2.825	30	100	0.55	Sweep mode test
	40	182	0.54	”
	50	283	0.54	”
4.03	30	108	0.58	Sweep mode test
	40	190	0.57	”
	50	290	0.56	..

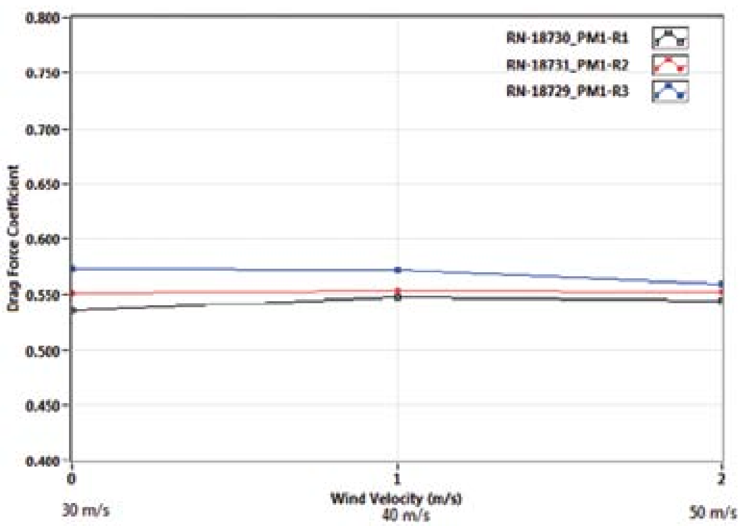


Figure 4. Effect of variation in the riser's length (single parachute without FB).

to 5 D (5 D, 7.5 D, and 10 D). According to this consideration, the test results for varying length of riser are shown in Table 6 and some subsequent Tables.

4.3 Test Results for a Single Parachute Behind the FB

The test was conducted with different riser's length viewing the wake effect on the parachute deployed behind the FB at side slip angles of 0, 5°, 10°, and 15° and the wind velocity ranges from 20 m/s to 50 m/s. The test results of this configuration are listed in Table 7.

Test results with a cluster of two canopy parachutes of the same configuration as used earlier (Table 7), is shown in Table 8.

The Tables 7 and 8 shows the test results even for the wind velocity as 20 m/s. The reason for the experimentation at this low value of wind velocity was carried out with a very conservative mind set to visualise the dynamic behaviour of the parachute at such low wind speed under FB wake.

The present study is for re-entry module of manned space mission. The earlier successful manned missions had

Table 7. Wind tunnel test results for a single parachute behind FB at different riser's length (under sweep mode)

Wake distance (m)	Beta angle (β) (degree)	C_d
L = 5 D	0	0.52-0.47
	5	0.50-0.47
	10	0.50-0.51
	15	0.49-0.51
L = 7.5 D	0	0.58-0.57
	5	0.58-0.60
	10	0.61-0.56
	15	0.52-0.57
L = 10D	0	0.57-0.55
	5	0.57-0.54
	10	0.57-0.54
	15	0.55-0.54

Table 8. Wind tunnel test results for a cluster of two parachutes behind FB at different riser's lengths (under sweep mode)

Wake distance	Beta angle (β)	C_d
L = 5 D	0	0.52-0.54
	5	0.53-0.57
	10	0.52-0.57
	15	0.53-0.56
L = 7.5 D	0	0.57-0.59
	5	0.57-0.59
	10	0.58-0.59
	15	0.58-0.59
L = 10 D	0	0.59-0.61
	5	0.59-0.61
	10	0.59-0.61
	15	0.59-0.61

the wake length greater than or equal to 5 D. Few of them are listed in Table 9.

It has been mentioned earlier that C_d of the combined system of FB and parachute(s) should be in the range of (0.5, 0.55). Looking at Tables 7, it can be observed that when wake distance is 5 D, C_d value for a single canopy parachute case is not within the desired range. Therefore, this combination cannot be accepted particularly in space mission where the cost of the mission is very high. Even though high wake distance as 7.5 D or 10 D results in high C_d value even on the better side of the desired range. But same is not being preferred as it will asked for more weight associated with high cost of mission without giving any significant advantage. In space mission, particularly with re-entry mode, the reliability of the operation is also to be looked into seriously[22]. From this perspective and optimum rate of descent, a cluster of two canopy parachutes is being suggested because the test results show the obtained C_d value (0.52, 0.57) even on the higher side of the desire range i.e. (0.5, 0.55).

The performance of the parachute in terms of dynamic stability for single (Fig. 5) and cluster of parachutes at different riser's length behind the FB (Fig. 6), at wake distance 5D and various side slip (beta) angles are determined from the wind tunnel study and found to be dynamically stable and within the acceptable range.

The above Figs. 5 and 6 clearly shows that the design configuration of the FB and parachute do not have dynamic stability issue at 5D wake distance and side slip angles.

Table 9. Worldwide wake distance chosen for various space mission and reported wind tunnel data

Mission	Maximum diameter of FB, *D*	Parachute diameter D_0	Suspension line length L_e	Riser length, *R*	Wake distance In terms of maximum FB diameter (m)
Orion[6]	4.912 m	7.06 m	14.22 m	16.47 m	6.22 D
Apollo[18]	3.911 m	5.06 m	10.16 m	9.65 m	5 D
SRE[19]	2.031 m	2.82 m	2.82 m	6.5 m	4.6 D

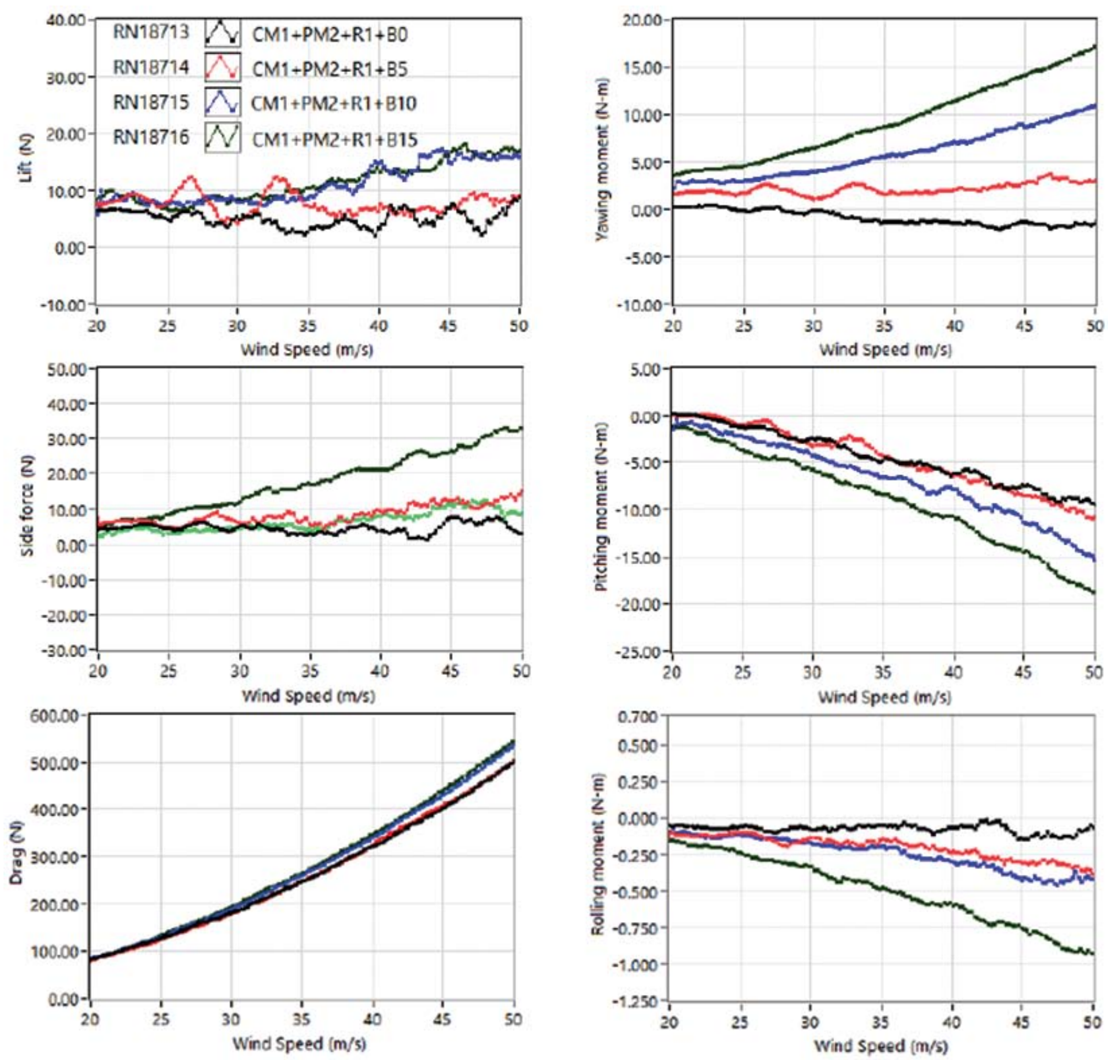


Figure 5. Wind axis forces and moments of single parachute with FB at riser length *R* = 1.26 m (β = 0° to 15°).

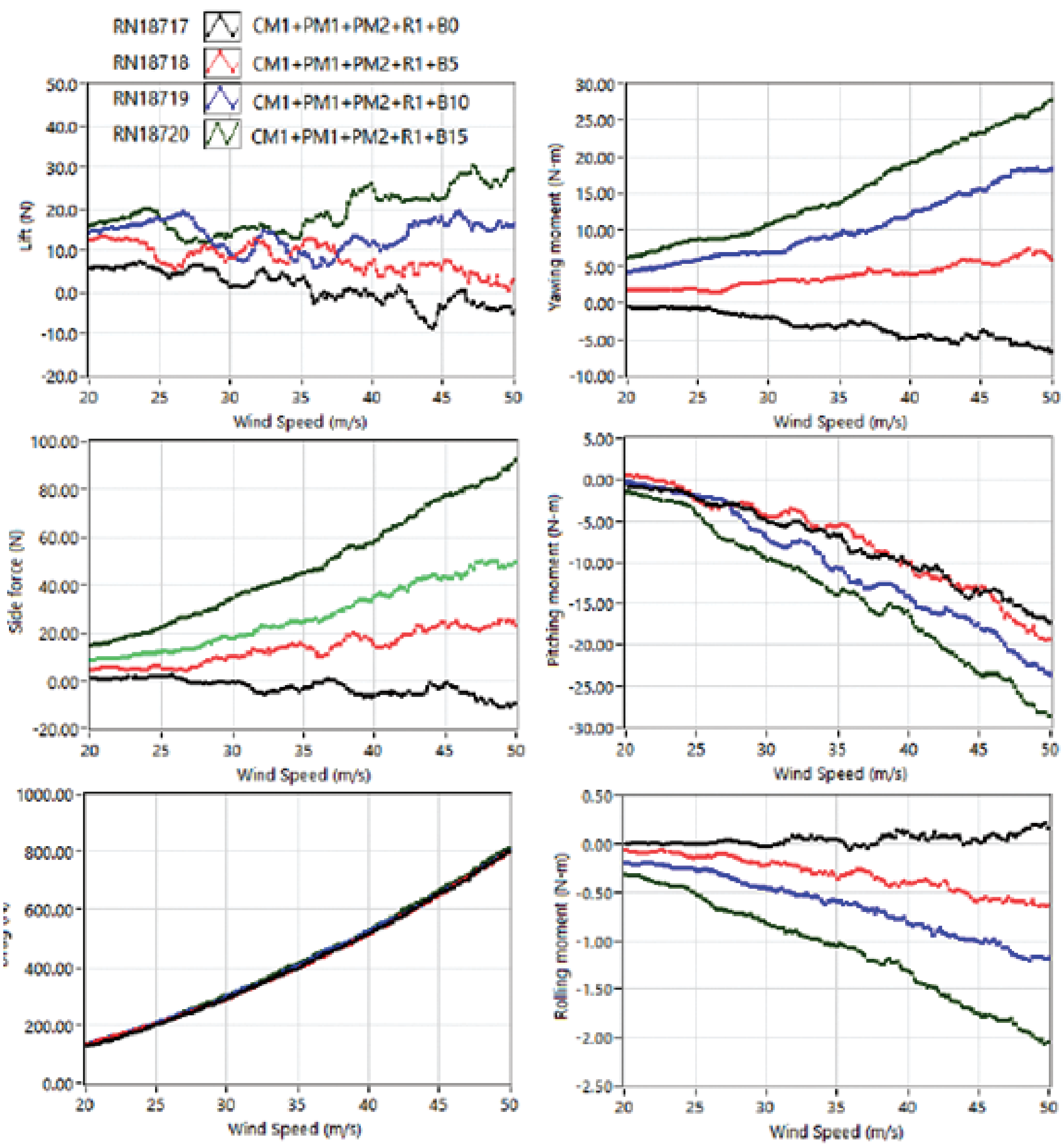


Figure 6. Wind axis forces and moments of cluster parachute with FB at riser length R = 1.26 m (β = 0° to 15°).

This is a clear indication that the chosen geometry of the FB and parachute is meeting the required specifications of the space mission program.

5. CONCLUSIONS

Forebody has been found to cause wake effect on the performance of the attached parachute(s) that has to serve as a decelerator. The wake effect is also dependent on orientation of FB and riser length. In the present study, FB is taken as a truncated cone with a spherical nose cap and the parachute to be 20-degree conical ribbon parachute with 24 gores. The study is aimed to determine a suitable configuration of FB and parachute for safe mission operation with re-entry module. The performance of the combinations in terms of varying side slip angle, riser length and use of twin parachute has been analysed by conducting wind tunnel test. The wind tunnel test was carried out on scaled down model of both the FB and the parachute (s).

The test results show that the use of single parachute may serve the purpose but will require riser of more length, but reliability will be an issue. Instead, the test-result finds the use of a cluster of two parachutes to yield satisfactory performance. Besides, this configuration will have a better mission reliability as was witnessed in Apollo mission. The test results also show that the configuration chosen for the forebody or the parachute does not have any dynamic stability problem.

This study may guide future efforts to improve the experimental and computational prediction techniques and further the fundamental understanding of forebody parachute complex dynamic stability.

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CONTRIBUTORS

Mr Mahendra Pratap is working as Scientist 'F' at DRDO-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 & quality assurance, testing and evaluations. He has been awarded Lab young scientist and Group Technology awards.
Contribution in the current study, he did design, testing and evaluation of parachute, modification(s), dynamic and flight tests.

Prof. Anil K. Agrawal is working as Professor in the Department of Mechanical Engineering, IIT (BHU), Varanasi, India. His area of interest are : Reliability, quality control, six sigma, optimisation, industrial engineering, operation management, and supply chain management.
Contribution in the current study, he has extended supervision to the main author for the analysis, outline of the research work, analysis of the results, design parameters, literature survey and final scrutiny of the paper.

Dr Subhash Chandra Sati is presently working as DRDO Chair at DRDO-Research & Development Engineers (E), Pune. His areas of interest are: Design, analysis, simulation and realisation of electro hydraulic control system, bond graph based modeling, 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 guided the entire project, interpretation of results and testing data, finalising the configuration, analysis, paper writing and review of this paper.

Mr Vipin Kumar Verma is working as Scientist 'E' at DRDO-Aerial Delivery Research & Development, Agra. His areas of interest are: Design of various personnel parachutes and wind tunnel testing.
Contribution in the current study, he executed the wind tunnel model testing, performed results iterations and compiled the test results.