Comparison of the Accuracy and Applicability of Forebody Wake Effect Models for Parachute System Design

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The forebody wake effect (FWE) is important to consider when designing parachute systems because it can affect parachute performance. Parachutes work by altering the aerodynamic properties of an attached forebody to control a descent. The FWE can reduce parachute drag, causing the system to descend faster than desired. This drag reduction coupled with wind or other factors can change the descent trajectory and landing impact speed. Modeling the FWE is important for ensuring that the parachute system descends and lands safely at the desired location. In the available literature there are three prominent FWE models for parachute system design. These models fall under two general modelling methods. The first method is to generate a statistical or empirical model based on a high number of full-scale experimental flights or tests. The second method is to create a case specific model with computational fluid dynamics(CFD). The goal of this paper is to explore the limitations and appropriate uses of the existing FWE models. Their applications and limitations were evaluated and compared in terms of modelling method, accuracy in determining drag reduction and breadth of situational applicability. The investigation showed that the models are applicable in specific design cases and vary in accuracy. The three models presented have different strengths and limitations, as expected. This review lays the foundation for developing a more comprehensive FWE model for parachute system design.

I. Nomenclature

q_{fb} = Dynamic pressure for parachute in a forebody wake
q_{∞} = Freestream dynamic pressure
$C_{d_{fb}}$ = Parachute coefficient of drag in forebody wake
C_{d_0} = Parachute coefficient of drag without attached forebody
U_{fb} = Relative air velocity flowing into parachute with forebody
U_{∞} = Relative air velocity in the freestream
ρ = Air density
A = Projected parachute area
F_d = Drag force

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II. Introduction

Parachute drag may be significantly altered due to a low-pressure zone downstream of the attached forebody. This can have undesirable effects on the descent of the parachute system. Effects include preventing parachute inflation and causing the system to descend at an increased velocity. This low-pressure zone is the result of the forebody wake effect(FWE). This wake zone extends downstream from the forebody towards the parachute canopy. The turbulent wake behind a forebody is characterized by lower streamwise velocity and lower dynamic pressure compared to the freestream airflow outside of the wake [1]. Fig. 1 shows an example wake profile. The resultant drag loss is characterized by the ratio of the parachute's coefficient of drag with a forebody to its coefficient of drag in a clean wake. Drag loss may also be represented by the ratio of dynamic pressure of a parachute with a forebody to the freestream dynamic pressure as shown in eq. (1).

$$Drag\ loss\ due\ to\ FWE = \frac{q_{fb}}{q_\infty}\ or\ \frac{C_{d_{fb}}}{C_{d_0}} \tag{1}$$

$$where\quad C_d = \frac{F_d}{\rho A \frac{U^2}{2}} \tag{2}$$

$$and\quad q = \frac{1}{2}\rho U^2 \tag{3}$$

The drag reduction caused by the FWE can be small or very large depending on conditions. One example of a large drag loss is seen during flight tests of NASA's forward bay cover parachute (FBCP) paired with their parachute test vehicle (PTV). The drag coefficient was reduced by 22% due to the PTV forebody [2]. From this example and eqs. (2) and (3), it is clear the drag loss cannot be neglected as it may be significant. Many parameters affect the FWE. Factors include but are not limited to parachute-forebody separation distance, Mach number, total angle of attack, projected parachute diameter, forebody diameter, overall forebody shape, and if the forebody includes fins [2,3]. Several models have been created to understand the factors of the FWE.

In the available literature, seven predictive FWE drag loss models were identified [1,2,3,4,5,6,7]. The models vary largely in terms of what situations they may be applied to, their accuracy, and their limitations. In this study, three models are selected and examined [1,2,8]. The objective of this study is to identify the applicability, accuracy, and limitations of existing models for parachute design. Four research questions will be considered to accomplish the objective:

RQ1: In what situations can the FWE models be applied?
RQ2: What is the accuracy of each model?
RQ3: What are other limitations of existing FWE models?
RQ4: Which of these limitations prevent development of a more comprehensive model for the FWE?

III. Background

The first challenge of the FWE is that in certain cases, the FWE causes extreme parachute drag reduction to occur. This may result in a temporary or sustained failure to fully inflate [9,10]. Secondly, the FWE can increase the descent velocity compared to the theoretical velocity of the parachute with no forebody wake. This could result in a higher speed ground impact that may compromise any onboard people or payloads. Furthermore, a faster descent may alter the descent trajectory, endangering the lives of any bystander in the descent path. Modeling the FWE is important for ensuring a safe and predictable descent.

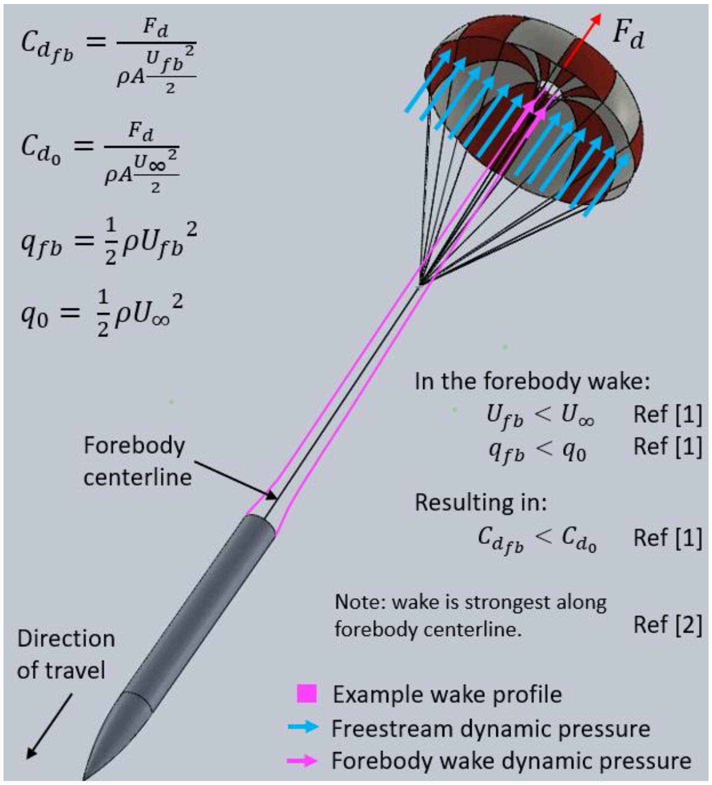

Fig. 1: Characteristics of the forebody wake effect. Adapted from [2], model used with permission from Fruity Chutes, Inc.

Based on the available literature, a predictive model of a forebody wake was first developed in 1959 by Heinrich and Riabokin [7]. Their model examined the turbulent wake behind ogive-nose cylindrical bodies of revolution. Based on wind tunnel measurements, velocity distribution equations were determined. The data from this study are used in the subsequent Heinrich and Eckstrom model [6]. In 1963, Heinrich and Eckstrom created an improved drag loss model which described the turbulent wake using four experimental forebody-dependent constants. A generalization was made to map the forebody constants to other bodies with the same coefficient of drag. While they found the generalized model to agree with their experimental data, a later study by Peterson and Johnson did not reach the same conclusion upon testing the Heinrich and Eckstrom model [1].

In 1983, Peterson and Johnson measured the drag of a 20-degree conical ribbon parachute behind an ogive cylinder forebody in a wind tunnel [1]. The forebody had removable fins. Measurements were taken for several angles of attack and at different parachute-forebody separation distances. For a control, parachute drag measurements were also taken for the parachute with the forebody removed. Based on the wind tunnel measurement data and legacy data from previous studies, Peterson and Johnson modified the Heinrich and Eckstrom model to predict drag loss more accurately. The study compared the new model to the two predecessor models from Heinrich and Riabokin, and Heinrich and Eckstrom. Peterson and Johnson concluded that both previous models were not capable of accurately predicting drag loss without experimentally re-deriving the four wake constants to match the forebody in question.

NASA took a more direct approach to determine drag loss for the Orion parachute system. In 2012, Phil C. Stuart created the CFD-based Orion drag loss model [2]. This is a general wake model for the Orion forebody. It was built by analyzing CFD solutions of detached eddy simulations (DES). The model is a series of look-up tables which determine drag loss based on Mach number, total angle of attack, parachute-forebody separation distance, and projected parachute diameter [2]. The NASA CFD model was in use up until the creation of the NASA Statistical model. After the transition, the NASA CFD model was used for pilot parachute drag simulations only. The replacement NASA statistical model is based on a library of data from different sources including drop tests, wind tunnel tests, and simulation data [2]. The NASA statistical model follows a complicated multi-step data processing method to determine the drag for all descent stages of the Orion capsule.

In summary, the Heinrich and Riabokin, and Heinrich and Eckstrom models were influential for developing the Peterson and Johnson model. The NASA CFD, and NASA statistical models use different and more direct approaches to estimate the drag loss due to the FWE. Each model is built for a different purpose and on different test data. Goals of the models range from creating a generalized model for arbitrary forebodies [1] to predicting drag loss with respect to different parachutes for a specific Orion capsule forebody [2].

IV. Method

Of the seven models identified in literature [1,2,3,4,5,6,7] three were selected for comparison and analysis. The models considered are the Peterson and Johnson [1], NASA CFD [2], and NASA Statistical [2] models. These models were selected for several reasons. For one, all selected models were previously or are currently used for parachute system design. The selected models are intended to comprehensively model the FWE drag reduction based on all known factors, rather than analyzing contributions of a single factor. Secondly, the chosen models are the most developed in terms of knowledge foundation with previous studies informing them. The selected models include a greater number of drag reduction factors and are more specific than some of their predecessors. In summary, the models were selected because they appear to be the most representative and developed sample of current design-oriented models.

The selected models are compared in terms of three major areas. These areas include known FWE drag reduction factors, model composition method, and model accuracy. Known parameters that affect the quantity of FWE drag reduction are divided into three categories. These categories include forebody, parachute, and system level parameters. Model composition characteristics are divided into four categories and emphasize the lack of a standard composition method. Model accuracy statements are largely based on information within the respective journal paper for each model. This is due to a lack of follow up studies. The exception to this is the Peterson and Johnson model, which was followed up by another study.

The FWE drag reduction factors, model composition characteristics, and model accuracy characteristics are intended to represent the state-of-the-art knowledge about the FWE and show the different modeling approaches. The full comparison tables are included in appendix tables 1-6. However, all data is not available for all models. Specifically, much of the data for the NASA CFD model is unavailable due to a restriction by the International Traffic and Arms Regulations on the paper that explains the model [8]. Despite the lack of information, the NASA CFD model is included because it is the most advanced and comprehensive CFD FWE model that exists in the available literature.

V. Results

To identify the applicability, accuracy, and limitations of existing models for parachute design questions, the three selected models were examined. Each model was found to be applicable in different scenarios corresponding to the purposes for which they were built. Table 1 shows the differences in modeling methods. For each model, limitations exist that affect their accuracy and utility.

The Peterson and Johnson model can predict drag loss for arbitrary forebodies so long as the four empirical wake constants are experimentally identified for that forebody. Peterson and Johnson report that the drag loss predictions are in “good agreement” with the experimental measurements [1]. However, the model is limited in several facets as shown in table 2. The most notable limitation is that the four empirical wake constants must be determined for individual forebodies. Deriving these constants does not save time as the drag reduction can be directly determined through experimentation or CFD, ignoring the Peterson and Johnson theory entirely. However, in certain circumstances the coefficients for the Peterson and Johnson model do not need to be re-derived to predict drag loss; this is the most notable success of the model. Drag loss can be predicted for multiple angles of attack using the same constants [1]. As shown in table 2, drag loss may be predicted for moderate angles of attack up to a threshold where the accuracy decreases [1]. This threshold is governed by forebody geometry and the lift that the body produces [1]. For this reason, finned forebodies have a lower limit than non-finned forebodies.

The NASA statistical model can predict drag loss for with the Orion Capsule forebody under four parachute descent stage configurations with varied reefing amounts at each stage. Parachute configuration details are shown in table 3. One notable advantage of the model is that it can be applied for several parachute configurations, rather than one, as is seen in the Peterson and Johnson model. Another notable advantage of this model method is that drag loss predictions for the Orion forebody are made using data from other forebodies. This model method poses a significant advantage, as it allows for accurate extrapolation of existing drag loss data. However, it should be noted that predictive capabilities of the statistical model are still limited by the parameters of the collected data.

The NASA CFD model was the predecessor to the NASA statistical model and had the same objective. The CFD model possessed some advantages over the statistical model, however the CFD model had significant accuracy problems which likely motivated the transition to the statistical model [2]. Advantages of the CFD model include that only simulations are required, rather drop tests or other flight tests. Another advantage of the CFD model is that drag reduction is determined based on independent variables, rather than indirectly as in the statistical model [2]. This allows one to more easily identify trends based on individual parameters. The accuracy problem of the CFD model is caused by the assumption that the parachute would remain centered downstream from the forebody (in the strongest part of the wake). Through experimentation, the parachute was shown to oscillate around the center position or remain uncentered for the entire decent [2]. Because of this, the CFD model overestimated drag reduction [2].

When using any drag prediction model, all FWE drag reduction factors must be considered for accurate predictions. Models based on a one parameter range may fail to predict results for a different range. For example, studies have shown that the wake has different characteristics far away from the forebody [1,7]. Furthermore, other studies have shown that the Mach number significantly influences drag loss, exhibiting a sharp drop in approaching Mach 1[3].

Irrespective of the model, special attention should be paid when extrapolating data across parameter ranges that are known to cause significant changes in drag reduction. As an example, data for Mach 0.2 should not be used for Mach numbers approaching 1. A summary of parameters and how they affect drag loss can be found in table 6.

VI. Discussion and Conclusion

The forebody wake effect is important to consider when designing parachute systems because it can affect parachute performance. Modeling the FWE is important for ensuring that the parachute system descends and lands safely at the desired location. The limitations and appropriate uses of existing FWE models were explored. Their applications and limitations were compared in tables 1-6 in terms of of modelling method, accuracy in determining drag reduction, and breadth of situational applicability. The investigation showed that the models are applicable in specific design cases and vary in accuracy. The presented models have different strengths and limitations, as expected.

Table 1 in the appendix shows the diversity of FWE modeling approaches and illustrates that there is not one standard method. The NASA statistical model method appears to be the most useful in terms of parachute system design. However, the statistical model method is inaccessible without a large library of relevant drop test information. This poses a problem for new, untested designs. In general, FWE drag loss models are limited by our understanding of the turbulent wake [1]. There is much work to be done to improve our understanding of turbulence so that higher quality models may be created.

Future research suggestions include following the methodology of the Peterson and Johnson model to derive the four empirical wake constants for more forebodies so that drag loss may be accurately predicted. Instead of deriving constants using wind tunnel testing, one could derive the constants using CFD. Taking advantage of state-of-the-art CFD software, a CFD wake solution library could be obtained for many forebodies. Once sufficient CFD solutions have been run, it may be possible to predict the empirical wake constants with greater accuracy than was previously possible with the limited amount of wind tunnel data. Likewise, a statistical analysis of the CFD wake solution library could also be used to build the model. Implications of a CFD wake solution library-based include predicting drag loss for new designs without the need for drop tests or other flight testing.

Other future research suggestions include using CFD to model the natural dynamic events that occur throughout the parachute system descent. Examples of these phenomena include parachute breathing, and transverse motion of the parachute relative to the forebody [2]. While the NASA statistical model indirectly incorporates in-flight dynamic events, future research should be conducted to increase the understanding of dynamic in-flight events.

Appendix

Table 1: Model Creation Method Comparison

		Model Method Characteristic				**Citation**
		Data type	Collection facility	Data collection method	Data Analysis Method	
Model	Peterson and Johnson	Pressure	Wind tunnel	Moveable multiple Pressure port apparatus, load cells	Mathematical correlation	[1]
	NASA PRF CFD	Navier-Stokes solver output (CFD)	Computer	simulation	Mathematical correlation	[2]
	NASA Stats	Flight test: pressure, force Wind tunnel	various	(list the various methods) Pressure ports Load cell	Statistical Correlation	[2]

Table 2: Model Accuracy and Limitations

		Model Characteristic		**Citation**
		Capable of modeling transverse parachute motion	Drag reduction notes on accuracy and limitations	
Model	Peterson And Johnson	No	• The modified theory (Peterson and Johnson theory) agrees with experimental drag loss data at 0 angle of attack because the empirical wake constants were adjusted to match the experimental velocity distributions. • Accurate predictions of parachute drag loss can be expected if an accurate method for turbulent wake velocity.” • No theoretical predictions are accurate for 20 degrees angle of attack. • For the non-finned forebody, the maximum forebody angle of attack where the theory can be accurately applied was approximately 10 degrees. • Lower maximum angle of attack for finned forebodies	[1]
	NASA CFD	No	• The model assumes parachutes are centered in the strongest part of the wake. This overestimates wake strength. • A Pilot parachute is not likely to be to reside at the minimal pressure recovery fraction (PRF) coordinate (i.e. in forebody wake center) because the parachutes are ejected nearly perpendicular to the velocity vector and the parachute group tends to remain spread out.	[2]
	NASA Statistical	Yes (indirectly)	• Test data showed more oscillations than the simulated output due non-modeled effects such as changes in canopy (deformations), turbulence in the forebody wake, and transverse (line) motion of the parachute.	[2]

Table 3: Parachute Parameters

<table>
<tr><th colspan="2" rowspan="2"></th><th colspan="2">Parachute Parameter</th></tr>
<tr><th>Projected Diameter</th><th>Geometry</th></tr>
<tr><td rowspan="3">Model</td><td>Peterson and Johnson</td><td>15 in.</td><td>20-degree conical ribbon</td></tr>
<tr><td>NASA CFD [2]</td><td>Not Available*</td><td>Not Available*</td></tr>
<tr><td>NASA Statistical [2]</td><td><table>
<tr><th>Parachute Name</th><th>Dp</th></tr>
<tr><td>FBCP</td><td>4.9 ft.</td></tr>
<tr><td>Drogue</td><td>8.73, 11.59, 16.10 ft.</td></tr>
<tr><td>Pilot</td><td>6.9 ft.</td></tr>
<tr><td>Main</td><td>9.87, 19.52, 81.20 ft.</td></tr>
</table></td><td>Various</td></tr>
<tr><td colspan="4"><u>Notes</u>

* Much information is no longer available due to International Traffic and Arms Regulation (ITAR) restrictions on access to the “Orion Crew Module Pressure Recovery Fractions” paper [8].</td></tr>
</table>

Table 4: Forebody Parameters

<table>
<tr><th colspan="2" rowspan="2"></th><th colspan="3">Forebody Parameters</th></tr>
<tr><th>Geometry</th><th>Fin pattern</th><th>Diameter</th></tr>
<tr><td rowspan="3">**Model**</td><td>Peterson and Johnson [1]</td><td><table>
<tr><td>Model name</td><td>Peterson and Johnson data</td></tr>
<tr><td>1</td><td>Ogive cylinder</td></tr>
<tr><td></td><td>Legacy data: Heinrich and Eckstrom</td></tr>
<tr><td>A</td><td>Hollow Hemisphere (open to flow)</td></tr>
<tr><td>B</td><td>Disk</td></tr>
<tr><td>C</td><td>Cone, 75 degree</td></tr>
<tr><td>D</td><td>Cone, 55 degree</td></tr>
<tr><td>E</td><td>Cone, 42.5 degree</td></tr>
<tr><td>F</td><td>Cone, 30 degree</td></tr>
<tr><td>G</td><td>Hollow Hemisphere (closed to flow)</td></tr>
<tr><td>H</td><td>Ogive cylinder</td></tr>
<tr><td>I</td><td>Ogive cylinder with afterbody 1</td></tr>
<tr><td>J</td><td>Ogive cylinder with afterbody 2</td></tr>
<tr><td>K</td><td>Ogive cylinder with afterbody 3</td></tr>
<tr><td>L</td><td>Ogive cylinder with afterbody 4</td></tr>
</table></td><td>No fins
X fins
+ fins
⅄ fins

Legacy data: Heinrich and Eckstrom:
All bodies have No fins</td><td>4.5 in.

Legacy data: Heinrich and Eckstrom:
All diameters are 1.5 in.</td></tr>
<tr><td>NASA CFD [2]</td><td>Orion: Truncated cone, gently curved base</td><td>No fins</td><td>198 in.</td></tr>
<tr><td>NASA Statistical [2]</td><td><table>
<tr><td>Name</td><td>Description</td></tr>
<tr><td>Weight Tub/Smart Release</td><td>Flat plate</td></tr>
<tr><td>SDTV</td><td>Dart-like</td></tr>
<tr><td>MDTV</td><td>Dart-like</td></tr>
<tr><td>PCDTV</td><td>Missile-like</td></tr>
<tr><td>PTV</td><td>Orion with further height truncation</td></tr>
<tr><td>Orion</td><td>Truncated cone, gently curved base</td></tr>
</table></td><td><table>
<tr><td>Name</td><td>Type</td></tr>
<tr><td>Weight Tub/Smart release</td><td>No fins</td></tr>
<tr><td>SDTV</td><td>⅄ fins</td></tr>
<tr><td>MDTV</td><td>⅄ fins</td></tr>
<tr><td>PCDTV</td><td>+ fins</td></tr>
<tr><td>PTV</td><td>No fins</td></tr>
<tr><td>Orion</td><td>No fins</td></tr>
</table></td><td><table>
<tr><td>Name</td><td>Measure (in.)</td></tr>
<tr><td>Weight Tub/Smart Release</td><td>Various</td></tr>
<tr><td>SDTV</td><td>12.75</td></tr>
<tr><td>MDTV</td><td>24</td></tr>
<tr><td>PCDTV</td><td>106</td></tr>
<tr><td>PTV</td><td>198</td></tr>
<tr><td>Orion</td><td>198</td></tr>
</table>inches</td></tr>
</table>

Table 5: System Parameters

<table>
<tr><th colspan="2"></th><th colspan="3">System Parameters</th></tr>
<tr><th colspan="2"></th><th>Angle of attack (degrees)</th><th>Free stream velocity</th><th>Parachute-forebody separation distance</th></tr>
<tr><td rowspan="3">Model</td><td>Peterson and Johnson [1]</td><td>0, 10, 20</td><td>Subsonic</td><td>L/Dc = [1.0, 1.25, 1.5, 1.75, 2.0]
Where L is suspension line length and Dc is forebody diameter</td></tr>
<tr><td>NASA PRF CFD [2]</td><td>0</td><td>Subsonic, Supersonic</td><td>Not Available*</td></tr>
<tr><td>NASA Statistical model [2]</td><td>0</td><td>Subsonic, Supersonic</td><td>
<table>
<tr><th></th><th colspan="3">trailing distance (LT)</th></tr>
<tr><th>Parachute Name</th><th>Forebody: MDTV or Other</th><th>Forebody: PCDTV</th><th>Forebody: PTV and Orion</th></tr>
<tr><td>FBCP</td><td>43.6 – 62.8</td><td>10.3</td><td>5.5</td></tr>
<tr><td>Drogue</td><td>54.2-54.7</td><td>11.2-11.3</td><td>6.0-6.1</td></tr>
<tr><td>Pilot</td><td>N/A</td><td>7.7</td><td>4.1</td></tr>
<tr><td>Main</td><td>116.6-119.8</td><td>25.2-26.2</td><td>13.7-14.0</td></tr>
</table>
LT Measured in forebody diameters</td></tr>
<tr><td colspan="5"><u>Notes</u>
* Much information is no longer available due to International Traffic and Arms Regulation (ITAR) restrictions on access to the “Orion Crew Module Pressure Recovery Fractions” paper [8].</td></tr>
</table>

Table 6: General Effect of Drag Reduction Factors

		Effect on drag loss due to FWE (holding all else constant)		**Citation**
		Drag reduced ($\frac{C_{d_{fb}}}{C_{d_0}}$ ↑)	Drag increased. ($\frac{C_{d_{fb}}}{C_{d_0}}$ ↓)	
FWE Drag reduction factor	Fins	*	*	[2]
	Mach number	Approach Mach 1	Depart from Mach 1	[3]
	(Projected) parachute diameter	↓	↑	[2]
	Forebody diameter	↑	↓	[2]
	(Projected) parachute diameter/forebody diameter	↑	↓	[2]
	Parachute-forebody separation distance	↓	↑	[6,7,2]
	Angle of attack	*	*	[1]
	Position of parachute relative to forebody	Parachute lies in forebody wake zone	Parachute lies outside forebody wake zone	[2]

<u>Key</u>
↑ = increase
↓ = decrease
* = unclear: dependent on several parameters

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