COMPUTATIONAL AND EXPERIMENTAL DETERMINATION OF A LIGHT SPORT AIRPLANE LONGITUDINAL AERODYNAMIC DERIVATIVES TO BE IMPLEMENTED IN A FLIGHT SIMULATOR

Francisco Ribeiro Fonseca Reis, chicorfr@yahoo.com.br
Antonio Rafael da Silva Filho, arafael@ufmg.br
Igor Machado Malaquias, imalaquias@yahoo.com.br
Paulo Henriques Iscold Andrade de Oliveira, iscold@ufmg.br
Universidade Federal de Minas Gerais – Departamento de Engenharia Mecânica – Av Antonio Carlos, 6627 – Pampulha – Belo Horizonte – Minas Gerais – Brasil, CEP 31.270-901 – (PPGMEC) Programa de Pós Graduação em Engenharia Mecânica.

Dimas Abreu Dutra, d1ma5ad@gmail.com
Universidade Federal de Minas Gerais – Departamento de Engenharia Elétrica – Av Antonio Carlos, 6627 – Pampulha – Belo Horizonte – Minas Gerais – Brasil, CEP 31.270-901.

Abstract: *The accurate determination of airplanes aerodynamic derivatives is of major importance in order to implement flight simulators with realistic characteristics. However, although a variety of methods is available to do it, it is not an easy task to determine them. This paper will discuss and compare the longitudinal aerodynamic derivatives obtained from a light sport aircraft flight test campaign, computational aerodynamic codes and theoretical empirical calculations. Parameters such as results accuracy, analysis time, analysis and implementation difficulties as well as logistic problems will be analyzed.*

Keywords*: Aerodynamic coefficients, flight tests, flight simulator.*

1. INTRODUCTION

Flight simulators are an important tool for the development of aircraft flight characteristics, aircraft systems, software and hardware as well as for flight training purposes. However, the effectiveness of the simulation will depend on the accuracy of the airplane model implemented. Therefore, the correct determination of the airplane aerodynamic coefficients is of fundamental importance. It would be ideal to determine all the coefficients by means of flight tests. However, those can take weeks, are expensive, require an airfield as well as a reliable flight acquisition data system and are exposed to innumerous practical difficulties which can affect the final results. Alternative methods to determine those coefficients should use numerical aerodynamic simulation codes or theoretical calculations with the help of experimental data abacuses.

There are several aerodynamic codes which can calculate an entire airplane configuration very quickly such as those based on the panel or vortex lattice methods. Each code has its own limitations which depend on which theory simplifications or assumptions are considered. Other flow simulation codes which solve the Navier-Stokes equations with or without simplifications demand a huge processing power for an entire aircraft configuration and are beyond the scope of this paper.

Regarding the empirical-theoretical analysis, a massive amount of empirical data used to determine the airplane aerodynamic coefficients and largely used for design purposes is available in literature. Generally, these empirical data are presented in the form abacuses that are functions of the airplane characteristics and flight conditions. Empirical data have been validated along the years and, although limited to the test cases, they represent reliable information and can be used together with theoretical calculations in order to predict the aerodynamic characteristics of an airplane.

The Centre for Aeronautical Studies (CEA) of the Federal University of Minas Gerais performed a flight test campaign using the light sport airplane ACS-SORA. The objective of that campaign was to determine the airplane aerodynamic longitudinal derivatives in order to implement the airplane model in the flight simulator that is being developed at CEA. This paper will compare and discuss the results obtained from the flight test campaign with the results obtained using three different methods available at CEA which are two aerodynamic computer codes, VSAERO and CEA-VLM and an empirical theoretical method based on Etkin (1958).

2. THE FLIGHT SIMULATOR

The Center for Aeronautical Studies has developed a flight simulator to be used as a platform for the development of facilitated flight strategies considering the need for developing systems that allow the airplane to be trajectory controlled rather than being controlled by attitude, as it is done today. Adopting control systems assisted by computer, in special the systems fly-by-wire, it is possible to establish previously the control input that can allow the pilot to have the direct control of its trajectory. This would make piloting much more intuitive and would save time and money on the pilot training. The flight simulator was developed entirely in SIMULINK and uses Microsoft Flight Simulator as the graphic interface. The flight simulator is shown in Fig. 1. More information about the simulator can be obtained from Filho (2009).

Figure 1. CEA Flight Simulator Running.

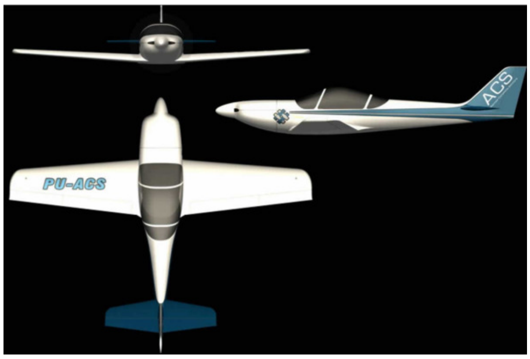

Figure 2. ACS-Sora Three Views Render.

The airplane that will be modeled in the flight simulator is the ACS-SORA which has been designed at CEA by the professor Cláudio Barros and is currently fabricated and sold by ACS Company. Currently a prototype is being constructed at CEA and will be used in the near future in the development of pilot assisted systems complementing the development achieved in the flight simulator. It is a high performance light sport airplane and its three views are shown in Fig. 2.

3. THE FLIGHT TESTS

3.1. The Hangar

The flight tests campaign was carried at the CEA hangar at the Bandeirinhas airport, Conselheiro Lafaiete – MG, Brazil. The hangar can accommodate comfortably fifteen people, has got a classroom, a meeting room, a kitchen, a mechanical garage and a telemetry room. This kind of infrastructure is of great value and has been essential to make it possible to accomplish the flight tests campaign in a reasonable time. The hangar is shown in Fig. 3.

Figure 3. Air View of CEA Hangar (on the right).

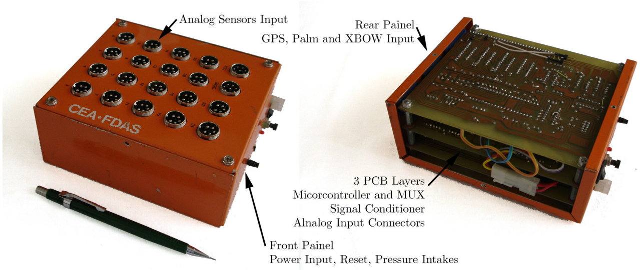

Figure 4. Final Hardware Assembly of the CEA-FDAS.

3.2. The Data Acquisition System

For the flight tests a data acquisition system developed at CEA, called CEA-FDAS, was used to collect the flights data. The development of this system was based on a microcontroller, chosen in accordance with main requirements of light aircrafts flight tests. The system uses the microcontroller in order to communicate with different kinds of sensors, including a GPS, and organizes this information to be sent to a PDA device, which is used to control the acquisition process and storage the data acquired. Details about the development of this system, including firmware algorithm and sensors development, are presented and discussed in Iscold (2005). The data acquisition system is presented in Fig. 4. The main characteristics of the equipment are:

- Portability. Light airplanes have limited space and payload weight.
- Easy operation. The operation of the system must be automatic, because light airplanes are mainly monoplace or biplace and it is difficult (and dangerous) for the pilot to operate both the aircraft and the FTI system.

- Low-cost. Light airplane production is usually limited to a small number of units, so, in order to avoid an increase in product cost, the system must not be expensive.
- Adaptability. The diversity of flight tests that can be made in a light airplane, involving different application areas (aerodynamics, flight mechanics, performance, etc.), requires that with just a few modifications in the sensors, and no modifications in the general architecture of the system, a large number of tests can be made.

3.2. The Flight Tests Campaign Planning

Although the flight test campaign was also planned to determine the airplane latero-diretional derivatives, only the maneuvers for the longitudinal derivatives, which are the focus of this paper, will be described. The maneuver consists in exciting the short-period mode using elevator doublets and 3-2-1-1 signals in order to excite the dynamics. The 3-2-1-1 consists, as the name implies, of a series of pulses, in opposite directions, of three times a basic time duration, followed by two times, one and one. Its' power spectrum excites a wider frequency band, providing more information on the parameters. For both signals, the duration of the shortest pulse was chosen to be around 1 second. Also were performed dutch roll and bank to bank maneuvers but those are not important for the scope of this paper.

All maneuvers were performed at cruise speed and with altitude around 2000 m above sea level (ASL). As this flight test campaign was the first time such techniques were used for aerodynamic parameter identification in this airplane, it was decided to be more careful on the execution of the maneuvers and parsimonious on the number of test conditions. In future campaigns, an envelope expansion will be carried out.

4. METHODS USED TO CALCULATE THE AIRPLANE LONGITUDINAL DERIVATIVES

After the flight tests, the airplane longitudinal aerodynamic derivatives were determined with two aerodynamic codes available at CEA, the commercial VSAERO and the in house developed code CEA-VLM as well as by the means of theoretical-empirical calculations.

4.1. Vsaero

VSAERO is based on a 3-D panel method using a Drichelet boundary condition formulation and is capable to compute the aerodynamic flow around an arbitrary body weather it generates lift or not. This approach permits the evaluation of the whole airplane assembly even for complicated geometries. Given the airplane geometry mesh, with a combination of sources and dipoles distribution over its surface and a dipole distribution over the wake, the potential Laplace equation is solved in each panel center and a potential velocity distribution is determined over the airplane. A boundary layer model is also coupled with the inviscid solution and solved iteratively through the displacement thickness or transpiration concepts. Integrating the pressure coefficients over the surface, the aerodynamic coefficients of the airplane can be calculated for a determined combination of pitch, yaw and roll angles at a specified air speed.

4.2. Cea-vlm

CEA-VLM is a non steady no linear 3-D vortex-lattice method based on the lifting line theory that can calculate the lift distribution along lifting surfaces provided the airfoils drag polars. This approach permits to evaluate the aerodynamic coefficients of almost any plan form wing and empennages at any combination of pitch, yaw and roll angles at a specified air speed. However, in this method, the fuselage influence is neglected. It is up to the user to consider if the results are representative or not for the studied case.

4.3 Theoretical-Empirical Calculations

The airplane aerodynamic derivatives were also estimated using the theory and several empirical abacuses, which are functions of the airplane geometry, and are presented in Etkin (1958). Those methods are widely used and well known; therefore, they won't be reproduced in this paper.

4.4 Flight Tests

To determine the longitudinal aerodynamic derivatives from the flight tests were used system identification techniques, for which the data collection was done with multistep input maneuvers. Separate maneuvers were performed for exciting the dutch roll, roll subsidence and short-period modes with frequency rich signals, as suggested by Jategaonkar (2006, Sec. 2.III.B). Before applying the inputs, steady state wings level horizontal flight was maintained for a few seconds.

Maximum likelihood (ML) methods were used to estimate the parameters from the acquired data. These methods are based on finding the set of parameters which maximize the probability that the data collected came from a model with those parameters. Two different formulations of ML were used to determine the longitudinal derivatives: the Equation Error Method (EEM) and the Output Error Method (OEM).

After investigating a few different model structures, an affine two-state dynamical model was chosen for the short-period mode. Its' states and outputs are the angle of attack (α) and the pitch rate (q); the input is the elevator deflection (η); and the affine parameters are nuisance biases (Z_b and M_b) that, essentially, make the equilibrium conditions unknowns to be estimated. The remaining unknown parameters were the elements of the state transition and input matrices, and are the dimensional stability and control derivatives. The equation governing equation for the longitudinal model is shown in Eq.(1).

$$\begin{bmatrix}\dot{\alpha}\\ \dot{q}\end{bmatrix}=\begin{bmatrix}Z_\alpha & Z'_q\\ M_\alpha & M_q\end{bmatrix}\begin{bmatrix}\alpha\\ q\end{bmatrix}+\begin{bmatrix}Z_\eta\\ M_\eta\end{bmatrix}\eta+\begin{bmatrix}Z_b\\ M_b\end{bmatrix} \tag{1}$$

An initial guess for the parameters was obtained using the EEM since, for models that are linear in the parameters, it can be used without any additional a priori information. The estimation with this method is reduced to a simple linear regression. This initial guess is usually not adequate enough, because the EEM assumes there is no noise in the measured data, which was not the case. These estimates were then refined using the OEM.

To apply the EEM, the angular accelerations and some signals' derivatives, which are not directly measured, are needed. Zero-phase filtering was then applied, to reduce noise, and the derivatives calculated with finite differences.

The OEM was used to further refine the estimates. Due to the integration inherent to this method, it was not necessary to calculate the derivative of any signal, which is usually more plagued by noise. The outputs of the models estimated for the short-period model can be seen, together with the data used for estimation, in Fig. 5.

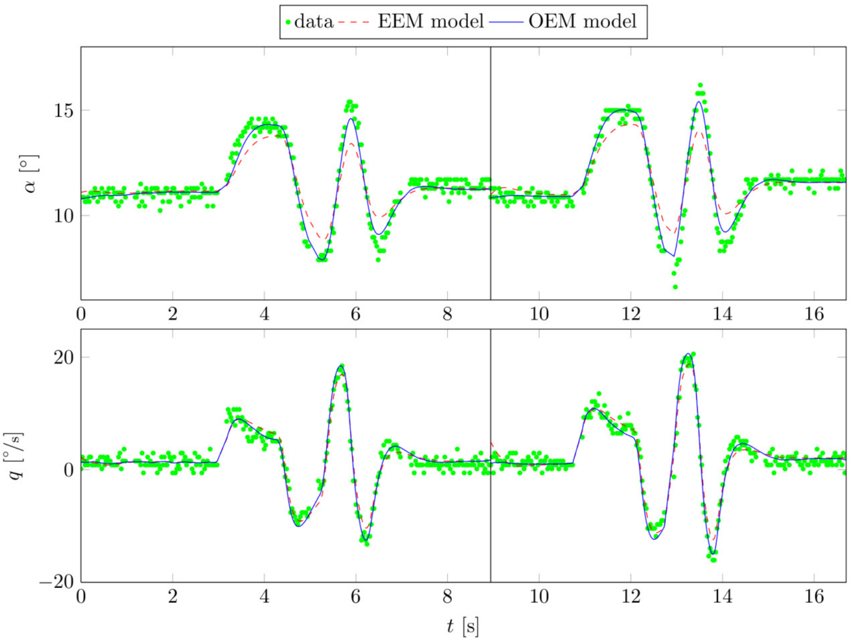

Figure 5. Output of the short-period models against the data used for estimation.

5. RESULTS AND ANALYSIS WITH THE PROPOSED METHODS

Before calculating the longitudinal derivatives using the acquired flight data a previous analysis was made in order to validate them. After the validation the derivatives were determined using the procedure proposed by Dutra(2010). In that work a mathematical model was developed to obtain the unknown aerodynamic derivatives from the data acquired during flight maneuvers.

5.1 Previous Analysis of Acquired Data

By analyzing the acquired flight tests data, it was possible to notice that the angles of attack measured were probably wrong. As shown in Fig. 6, the lift curve slope as well as the zero lift angle were very discrepant compared to the theoretical and numerical predictions. It is very likely that the flow direction indicator used during the tests was mounted on the wing with an incidence as it is shown in Fig. 7. Since this was noted only after the campaign, it was not possible to verify the incidence of the flow direction indicator. Since the zero lift angle was not important for the aerodynamic derivatives determination, no greater efforts were done to find a correction.

Although the hypothesis above would explain the error in the zero lift angle, it would not explain the error in the lift curve slope. After some analysis using the VSAERO code, it was found that the flow direction indicator was placed in a position upstream of the wing where the up-wash effect on the free stream was still important. As a result, the angles measured were always greater than the actual angle of attack. So being, the same code was used to calculate the up-wash in the flow direction indicator position and the results were used to correct the acquired data. As a result, the wing slope of the lift curve obtained with the corrected acquired data was in accordance with the predicted values as shown in Fig. 6.

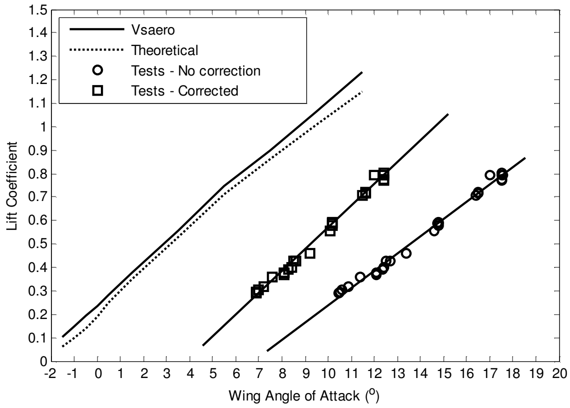

Figure 6. ACS-Sora Lift Coefficient Curve.

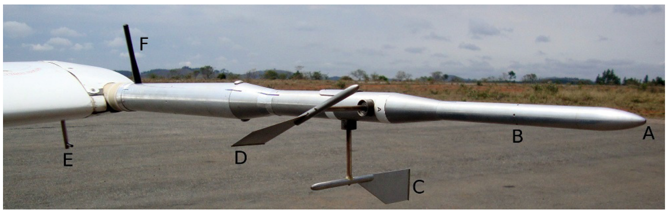

Figure 7. Flow Direction Indicator and Pitot Tube Used During the Flight Tests Campaign.

5.2 Determination of the Longitudinal Derivatives

The correction made, the longitudinal derivatives of the airplane were calculated provided the acquired data. Results are shown in Tab. 1. Figure 8 and Fig. 9 show the results of a simulation using the aerodynamic codes used. It is possible to see how the CEA-VLM code neglects the fuselage influence.

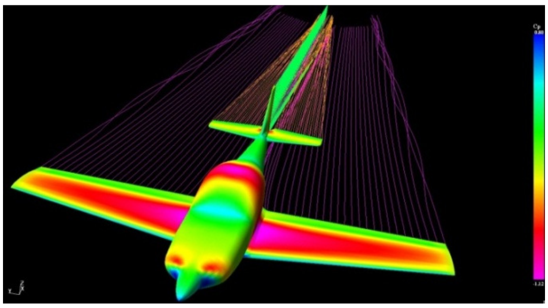
Figure 8. Snapshot of the Output Generated by VSAERO

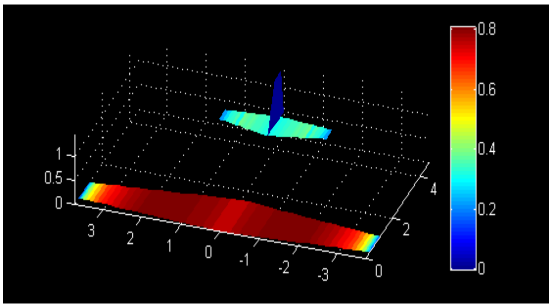
Figure 9. Snapshot of the Output Generated by CEA-VLM

Table 1. ACS-Sora Longitudinal Derivatives Determined From Flight Tests Data.

Test	$dC_L/d\alpha$ [1/rad]	$dC_M/d\alpha$ [1/rad]	dC_M/dq [s/rad]	dC_L/dq [s/rad]	$dC_M/d\eta$ [1/rad]	$dC_L/d\eta$ [1/rad]
1	No data	-0.57	-0.18	0.00	-1.26	0.00067
2	No data	-0.52	-0.18	0.00043	-1.17	0.00067
3	No data	-0.48	-0.18	0.077	-1.16	0.0015

4	No data	-0.49	-0.20	0.22	-1.35	0.00029
5	No data	-0.51	-0.20	0.035	-1.24	0.00015
6	No data	-0.53	-0.19	0.0025	-1.22	0.18
7	4.51	-0.70	-0.23	0.048	-1.54	0.00
8	4.69	-0.62	-0.21	0.050	-1.40	0.54
9	4.29	-0.65	-0.21	0.00031	-1.37	0.85
10	5.02	-0.73	-0.21	0.033	-1.41	0.00
11	4.21	-0.67	-0.21	0.016	-1.36	0.00015
STDDEV	0.32	0.09	0.017	0.064	0.12	0.29
MEAN	4.60	-0.59	-0.2	0.044	-1.32	0.14

The same derivatives were determined using the VSAERO code. Results are shown in Tab. 2.

Table 2. ACS-Sora Longitudinal Derivatives Determined With VSAERO.

$dC_L/d\alpha$	$dC_M/d\alpha$	dC_M/dq	dC_L/dq	$dC_M/d\eta$	$dC_L/d\eta$
5.01	-0.54	-0.11	0.26	-1.15	0.46

Using the theoretical-empirical analysis the derivatives in Tab. 3 were calculated.

Table 3. ACS-Sora Longitudinal Derivatives Determined From the Theoretical-Empirical Analysis.

$dC_L/d\alpha$	$dC_M/d\alpha$	dC_M/dq	dC_L/dq	$dC_M/d\eta$	$dC_L/d\eta$
4.96	-0.63	-0.13	0.12	-1.12	0.54

Using the CEA-VLM code the longitudinal derivatives were calculated and are shown in Tab. 4.

Table 4. ACS-Sora Longitudinal Derivatives Determined using the CEA-VLM Code

$dC_L/d\alpha$	$dC_M/d\alpha$	dC_M/dq	dC_L/dq	$dC_M/d\eta$	$dC_L/d\eta$
4.94	-1.17	-0.10	0.072	-1.59	0.55

A summary of the calculated derivatives is shown in Tab. 5.

Table 5. Summary of Calculated Aerodynamic Derivatives

METHOD	$dC_L/d\alpha$	$dC_M/d\alpha$	$dC_L/d\eta$	$dC_M/d\eta$	dC_L/dq	dC_M/dq
VSAERO	5.01	-0.54	0.46	-1.15	0.26	-0.11
THEORY	4.96	-0.63	0.54	-1.12	0.12	-0.13
CEA-VLM	4.94	-1.17	0.55	-1.59	0.072	-0.10
FLIGHT TESTS	4.60	-0.59	0.14(1)	-1.32	0.044(1)	-0.20

(1) Result obtained from very disperse data, probably not accurate. See Tab. 1.

6. CONCLUSIONS

Results above are reasonable and show that for most applications the three methods presented provide good estimates of the derivatives studied.

All methods predict accurately the $dC_L/d\alpha$ determined by the flight tests considering the tests standard deviation.

Regarding the $dC_M/d\alpha$, VSAERO and the theory were in accordance with the flight tests results. CEA-VLM overpredicted the result and that discrepancy is due to the fact that the code neglects the fuselage influence which contributes for the airplane moment coefficient.

The calculations of $dC_L/d\eta$ presented a good agreement between the methods used for the calculation. The theory and the CEA-VLM methods do not consider the influence of the body on the wing lift distribution and therefore provide a value 10% higher than VSAERO. The value determined by the flight tests is quite discrepant and obtained from very disperse flight data. It is reasonable to believe that the calculated values are more accurate than the measured one for that coefficient.

The $dC_M/d\eta$ derivative, all methods used and the flight tests result agree. Once again the CEA-VLM result is higher than the others for it neglects the fuselage moment. All results stay however very coherent.

Regarding the dC_L/dq derivative, all methods presented quite different values. Since the flight tests result was not validated for that derivative, no conclusion is possible.

Finally, all methods are in agreement for the calculation of the dC_M/dq derivative considering the flight test data standard deviation.

It has been shown that the derivatives estimated with the proposed methods are accurate. Considering the difficulties of flight tests performance and data interpretation of the calculated derivatives they provide valuable information and support to verify flight tests results.

7. ACRONYMS

CEA	Centro de Estudos Aeronáuticos.
CEA-FDAS	Centro de Estudos Aeronáuticos – "Flight Data Aquisition System".
GPS	"Global Positioning System".
UFMG	Universidade Federal de Minas Gerais.
PDA	Personal Digital Assistant .
ML	Maximum Likehood Method
OEM	Output Error Method
EEM	Equation Error Method

8. LIST OF SYMBOLS

C_L	Airplane lift coefficient.
C_m	Airplane moment coefficient.
q	Airplane pitch rate.
α	Airplane angle of attack.
η	Elevator's deflection.

9. REFERENCES

Dutra, D.A.D., Iscold, P.H.I.A., 2010, Identificação de Sistema para uma Aeronave Leve, Departamento de Engenharia Mecânica, Universidade Federal de Minas Gerais, Belo Horizonte, Brasil.

Etkin, B., 1958, "Dynamics of Flight". Ed. John Willey & Sons, New York, United States of America, 519 p.

Filho, A.R.S., 2009 "Desenvolvimento e Avaliação de Estratégias de Assistência à Pilotagem Para Aeronaves Leves". Dissertação apresentada no Curso de Mestrado do Departamento de Engenharia Mecânica da Escola de Engenharia da Universidade Federal de Minas Gerais, Belo Horizonte - MG.

Iscold, P.H.I.A., 2008, "Low-cost Flight Test System for Light Aircrafts". Aircraft Engineering and Aerospace Technology.

Jategaonkar, R., 2006, "Flight Vehicle System Identification: A Time Domain Methodology". AIAA.

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11. RESPONSIBILITY NOTICE