Journal of Research in Science and Engineering (JRSE)
ISSN: 1656-1996 Volume-7, Issue-10, October 2025
DOI: 10.53469/jrse.2025.07(10).05

Sensitivity Analysis of stage Separation Parameters in Launch Vehicles Utilizing Sobol Method

Haoqi Zhang[1,2,3], Qingtao Wang[1,2,3,*], Yifan Tong[1,2,3]

[1]School of Physics, Nanjing University of Science and Technology, Nanjing, China
[2]Institute of Launch Dynamics, Nanjing University of Science and Technology, Nanjing, China
[3]National Key Laboratory of Complex Multibody System Dynamics, Nanjing University of Science and Technology, Nanjing, China
**Correspondence Author*

Abstract: ***As a critical component of aerospace engineering, the stability and reliability of launch vehicles directly influence the success of space missions. During the launch process, stage separation is one of the essential steps that ensures the safe and smooth transition of the vehicle into space. This study aims to systematically assess the sensitivity of key parameters during stage separation using Sobol sensitivity analysis. A dynamic model for stage separation of launch vehicles is first established, accounting for uncertainties in physical parameters and forces acting on the vehicles. The sensitivity analysis focuses on various parameters including thrust, fuel sloshing, and center-of-mass offset. By calculating the Sobol indices for these parameters, their significance concerning displacements, attitudes and minimum clearance between stages during separation are quantified. The results indicate that residual thrust has a more substantial impact on axial displacement, roll angle, and minimum clearance than other factors. Additionally, offsets in the mass centers of both first and second stages significantly affect pitch angle, yaw angle, and radial displacement during this critical phase of the separation.***

Keywords: Parameter sensitivity analysis, Stage separation, Launch vehicle, Sobol method**.**

1. Introduction

A launch vehicle is a multi-stage, rocket-based space transportation system designed to deliver payloads into specified orbits. These payloads may include manned spacecraft, Earth-orbiting satellites, space stations, and space probes. Throughout the launch process, the vehicle systematically jettisons spent components through separation events including booster separation, stage separation and fairing separation. This reduction in mass facilitates a more efficient ascent of the payload. As a consequence, the stage separation plays a critical role in the operation of a launch vehicle, directly affecting both its performance and safety [1]. During this phase, the interactions between various parameters are intricate and multifaceted, and even slight variations in these parameters may lead to collisions between stages, potentially causing catastrophic failures during launch. Hence, it is imperative to perform a comprehensive sensitivity analysis of the parameters to ensure reliable mission performance.

Sensitivity analysis evaluates the response of a system to its parameters. The methodologies for sensitivity analysis can be broadly classified into two categories: local sensitivity analysis and global sensitivity analysis [2]. Local sensitivity analysis examines the individual effect of each parameter on the model consequences, making it particularly suitable for models with simple mathematical expressions and fewer sources of uncertainty. In contrast, global sensitivity analysis enables the simultaneous evaluation of the effects of individual parameters and their interactions on model results. In this approach, the sensitivity of a single parameter also considers the variation range and probability distribution of the other parameters. Compared to local sensitivity analysis, global sensitivity analysis provides a more comprehensive and insightful understanding of complex systems, supports optimized decision-making and improves model reliability. The Sobol method is a variance-based global sensitivity analysis technique that assesses the main effects, total effects of individual parameters, and interaction effects among multiple parameters on model. This method is highly effective in analyzing the sensitivity related to stage separation parameters in launch vehicles.

The Sobol method has been widely applied by numerous scholars across diverse fields. Sanio et al. [3] utilized this method to identify critical factors influencing the lifespan prediction of prestressed concrete bridges. Xin et al. [4] performed a global sensitivity analysis on two types of lithium-ion batteries, highlighting key parameters that improve both the accuracy and stability of state estimation for these batteries. Pan et al. [5] applied the Sobol method to evaluate the significance of equipment system support capability indicators in relation to combat effectiveness. Cao et al. [6] conducted a parameter analysis of the ENSO (El Niño Southern Oscillation) model in meteorology, and identified crucial important model parameters. Kumar et al. [7] used this methodology to assess the risks associated with uranium in groundwater, pinpointing the relevant parameters. Le Guyadec et al. [8] employed the Sobol method for a sensitivity analysis of thermal models of electric motors, providing essential insights for optimization adjustments. Zhou et al. [9] obtained factor sensitivities that emphasized the influence of various factors on brake performance, and established a surrogate prediction model for this process using Support Vector Machine (SVM). Xu et al. [10] analyzed the impact of various capability indicators on the operational effectiveness of naval air defense systems amid global changes, providing valuable references for evaluating air defense capabilities. Through the Sobol method, Ortega Pelayo et al. [11] conducted a global sensitivity analysis of pressure tubes using the Sobol method. Mao et al. [12] performed a multi-objective optimization design of outlet guide vanes for a diagonal flow fan, with Sobol sensitivity analysis forming the foundation of their work. Zhang et al. [13] examined the sensitivity of twelve thermal design parameters in a space manipulator joint thermal model through the Sobol method. Fuat and Ertekin [14] explored the effects of explosive parameters on the results of Sobol sensitivity analysis in underwater explosion simulations. Wang et al. [15] applied Sobol global sensitivity analysis to quantitatively assess the impact of four geometric design parameters and inlet volume flow rate on the performance of manifold microchannel heat sinks. Liang et al. [16] evaluated sensitivity indices related to extreme deviations in reactor core relative power, caused by uncertainties in heat transfer coefficients. Han et al. [17] utilized the Sobol method to identify critical geometric error terms, through sensitivity analysis. Vahid et al.18 applied the Sobol method to quantify the effects of parameters on bone drilling temperature and axial force, and enabled optimization of surgical drilling technology.

The Sobol method has been extensively employed in the aerospace industry. Xu et al. [19] developed a sensitivity analysis approach for nozzle parameters utilizing the Sobol method, which effectively quantified the impact of uncertainties in material and structural parameters on the thermal damage of solid rocket engine nozzles. Chen [20] confirmed the global sensitivity of aircraft state parameters through the application of the Sobol method. Wang et al. [21] proposed a computational framework for global sensitivity analysis based on the Sobol method, which provided significant references for future Earth-Moon transfer trajectory design and related engineering tasks. Song et al. [22] employed the Sobol method to derive sensitivity data for design parameters associated with the multi-objective constrained self-propelled ejection of rockets, subsequently optimizing their model accordingly. Liu [23] applied the Sobol method to evaluate the influence of uncertain parameters on an aircraft's altitude. Wang et al. [24] utilized the Sobol method to compute both first-order and total sensitivity of navigation and design parameters concerning energy consumption in underwater gliders, thereby identifying key factors that significantly affect energy consumption per profile. Yin et al. [25] proposed a global sensitivity analysis strategy based on the Sobol method, aimed at addressing issues related to the sensitivity of design variables within aircraft structural design.

In the domain of stage separation for launch vehicles, the application of the Sobol method in sensitivity analysis remains relatively infrequent. Therefore, this study aims to employ the Sobol method to conduct a sensitivity analysis of stage separation parameters in launch vehicles, thereby contributing valuable insights to this field. Specifically, this paper presents the development of a dynamic separation model for the stage separation of launch vehicles, created using Mworks software version [26].

A sensitivity analysis is conducted on various parameters including thrust, sloshing force, and center of mass offset, by the Sobol method. By calculating the Sobol indices for these parameters, their significance in relation to displacements, attitudes, and minimum clearances between stages can be quantified during the separation process, and the critical parameters that affect stage separation are identified. The subsequent sections of the paper are structured as follows. The governing principles of launch vehicle stage separation are analytically examined in Section 2. Section 3 provides a rigorous presentation of the Sobol method's theoretical basis and operational procedures. A parameterized separation model is developed in Section 4, where systematic sensitivity investigations are performed. Section 5 consolidates the principal research consequences and their significance.

2. Theoretical Model of Stage Separation in Launch Vehicles

Figure 1 presents a schematic illustration of the launch vehicle, comprising the first stage, second stage, satellite, and payload fairing. In this figure, the model for stage separation of launch vehicles predominantly comprises two rigid stages and a cold separation device. The centroids of the first stage, the second stage, and the entire launch vehicle are situated at locations ①, ②, and ③, respectively. The first and second stages of the launch vehicle are interconnected by explosive bolts positioned on the separation surface. Solid mini-rockets are utilized as the separation mechanism to produce both positive and reverse thrust in (Figure 1).

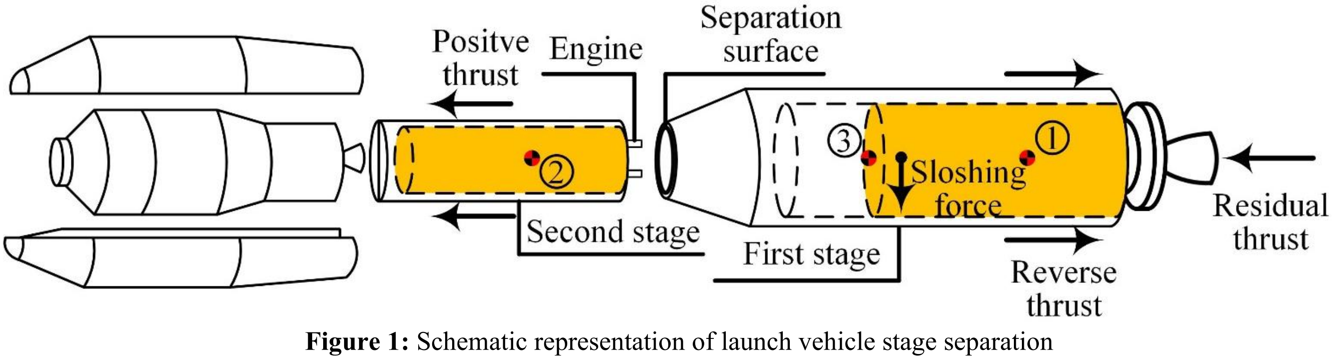


Figure 1: Schematic representation of launch vehicle stage separation

This paper is predicated on several assumptions. It is posited that the separation process is brief, lasting no more than 3 seconds, during which assumed that the masses of both stages, their center positions, and moments of inertia are considered to remain constant. Generally, at the moment of separation, the altitude of the launch vehicle exceeds 100 km. Therefore, aerodynamic forces are negligible.

The six degrees of freedom for the rigid bodies of the first and second stages of the launch vehicle include three positional coordinates and three angular coordinates. The dynamic equations that govern the motion of the first and second stages are expressed as follows

$$\begin{cases} \boldsymbol{M}_1 \ddot{\boldsymbol{x}}_1 = \boldsymbol{F}_1^{\mathrm{e}} + \boldsymbol{F}_1^{\mathrm{c}} \\ \boldsymbol{M}_2 \ddot{\boldsymbol{x}}_2 = \boldsymbol{F}_2^{\mathrm{e}} + \boldsymbol{F}_2^{\mathrm{c}} \end{cases} \tag{1}$$

where $\boldsymbol{M}_1$ and $\boldsymbol{M}_2$ represent the mass matrixes of the two stages, respectively. x_1 and x_2 represent the position coordinates of the first and second stages within the inertial coordinate system, respectively; $\boldsymbol{F}_1^{\mathrm{e}}$ and $\boldsymbol{F}_2^{\mathrm{e}}$ represent the external forces exerted on these two stages, which include positive thrust, reverse thrust, residual thrust and sloshing force. $\boldsymbol{F}_1^{c}$ and $\boldsymbol{F}_2^{c}$ represent the constraint forces generated by explosive bolts.

The rotational equations pertaining to the body-fixed coordinate systems of the first and second stages are given as follows

$$\begin{cases} \boldsymbol{I}_1\dot{\boldsymbol{\omega}}_1 + \boldsymbol{\omega}_1 \times (\boldsymbol{I}_1\boldsymbol{\omega}_1) = \boldsymbol{T}_1^{\mathrm{e}} + \boldsymbol{T}_1^{\mathrm{c}} + \boldsymbol{\rho}_1 \times \boldsymbol{F}_1^{\mathrm{c}} \\ \boldsymbol{I}_2\dot{\boldsymbol{\omega}}_2 + \boldsymbol{\omega}_2 \times (\boldsymbol{I}_2\boldsymbol{\omega}_2) = \boldsymbol{T}_2^{\mathrm{e}} + \boldsymbol{T}_2^{\mathrm{c}} + \boldsymbol{\rho}_2 \times \boldsymbol{F}_2^{\mathrm{c}} \end{cases} \tag{2}$$

where $\boldsymbol{I}_1$ and $\boldsymbol{I}_2$ represent the inertia matrix of the first and second stages around their respective centroids; $\boldsymbol{\omega}_1$ and $\boldsymbol{\omega}_2$ represent the projection vectors of the angular velocity vectors of the first and second stages onto their corresponding body-fixed bases; $\boldsymbol{T}_1^{\mathrm{e}}$ and $\boldsymbol{T}_2^{\mathrm{e}}$ represent the external torques applied to the first and second stages; $\boldsymbol{T}_1^{\mathrm{c}}$ and $\boldsymbol{T}_2^{\mathrm{c}}$ represent the constraint torques acting on each stage. $\boldsymbol{\rho}_1$ and $\boldsymbol{\rho}_2$ represent the projection vectors from points of application of the constraint forces to the centroids of both stages onto their respective body-fixed bases.

In this study, explosive bolts are utilized to replicate the constraints between the first and second stages of launch vehicles. These constraints are characterized by the absence of relative displacement at the points of constraint force application and the equality of the attitude angles between the two stages, which can be expressed as follows

$$\begin{cases} \boldsymbol{r}_1 - \boldsymbol{r}_2 = \boldsymbol{0} \\ \boldsymbol{\theta}_1 = \boldsymbol{\theta}_2 \end{cases} \tag{3}$$

where $\boldsymbol{\theta}_1$ and $\boldsymbol{\theta}_2$ represent the attitude angles of the first and second stages, respectively. This constraint equation becomes invalid following the separation.

3. Sobol Method

In the Sobol method, a model is formulated as a function that can be decomposed into multiple sub-functions, each representing different parameters and their interactions [27]. Let $Y = f(X)$, where $X = (x_1, x_2, \cdots, x_n)$ and $x_i (i = 1, 2, \cdots, n)$ are independent random variables uniformly distributed over the interval $[0, 1]$. $f(X)$ can be determined as follows

$$f(X) = f_0 + \sum_i f_i(x_i) + \sum_{i,j,i<j} f_{i,j}(x_i, x_j) + \cdots + f_{1,2,\cdots,n}(x_1, x_2, \cdots, x_n) \tag{4}$$

If $\int_0^1 f_{i_1, i_2, \cdots, i_s} dx_{i_p} = 0$ is satisfied, where $1 \le i_1 < i_2 < \cdots < i_s \le n$, $1 \le s \le n$, $1 \le p \le s$, the decomposition form of $f(X)$ is unique and referred to as the variance decomposition.

Each term in Equation (4) can be derived as follows

$$\int f(x) \prod dx_p = f_0 \tag{5}$$

$$\int f(x) \prod_{k \ne i} dx_p = f_0 + f_i(x_i) \tag{6}$$

$$\int f(x) \prod_{k \ne i, j} dx_p = f_0 + f_i(x_i) + f_j(x_j) + f_{i,j}(x_i, x_j) \tag{7}$$

By following this pattern iteratively, $f_{1, 2, \cdots, p}(x_1, x_2, \cdots, x_s)$ can be determined.

In the Sobol method, the effects of individual parameters and their interactions on the model are characterized as partial variances, respectively

$$D_i = \int f_i^2 dx_i \tag{8}$$

$$D_{i_1, i_2, \cdots, i_s} = \int f_{i_1, i_2, \cdots, i_s}^2 dx_{i_1} dx_{i_2} \cdots dx_{i_s} \tag{9}$$

Accordingly, the effect of all parameters on the model is represented by the sum of D_i and $D_{i_1, i_2, \cdots, i_s}$, which can be derived by squaring and integrating Equation (4), as follows

$$D = \sum_{i=1}^{n} D_i + \sum_{i=1}^{n} \sum_{j=1, i \ne j}^{n} D_{i,j} + \cdots + D_{1, 2, \cdots, n} \tag{10}$$

By normalizing Equation (10), the sensitivities of individual parameters and interactions between them can be obtained as follows

$$S_i = \frac{D_i}{D} \tag{11}$$

and

$$S_{i_1, i_2, \cdots, i_s} = \frac{D_{i_1, i_2, \cdots, i_s}}{D} \tag{12}$$

respectively, Equation (13) can be expressed as follows

$$1 = \sum_{i=1}^{n} S_i + \sum_{i=1}^{n} \sum_{j=1, i \ne j}^{n} S_{i,j} + \cdots + S_{1, 2, \cdots, n} \tag{13}$$

where S_i represents the first-order sensitivity index and $S_{1, 2, \cdots, n}$ represents the nth-order sensitivity index, representing the effect of the interaction of n parameters on the model.

The global sensitivity index for a single parameter is defined as the sum of the sensitivity indices that take this parameter into account, which can be calculated as follows

$$S_{T_i} = 1 - S_{1-i} \tag{14}$$

where S_{1-i} represents the sensitivity of the model response to all design parameters except for the parameter i.

This study utilizes the Sobol method and applies a sensitivity analysis framework based on the Monte Carlo method [28] to conduct a thorough sensitivity analysis of the stage separation parameters pertinent to launch vehicles.

4. Simulation Examples and Results Analysis

4.1 Simulation Model

Based on the previous work of the authors [29], in this study a model is developed to analyse the stage separation of launch vehicles. The x-direction is defined as the axial direction of the launch vehicle, while the y- and z-directions are designated as the circumferential directions. A specific model for stage separation is established in accordance with the underlying hypotheses and principles governing this process.

Figures 2-4 illustrate the modules of the stage separation model constructed within Mworks.

In Figure 2, the module of the first stage includes the rigid body of the first stage, reverse thrust, sloshing force, and residual thrust. In Figure 3, the module of the second stage comprises the rigid body of the second stage, the engine, and positive thrust. These modules are linked by an explosive bolt mechanism, facilitating the creation of a simulation model for the stage separation of the launch vehicle, (Figure 4).

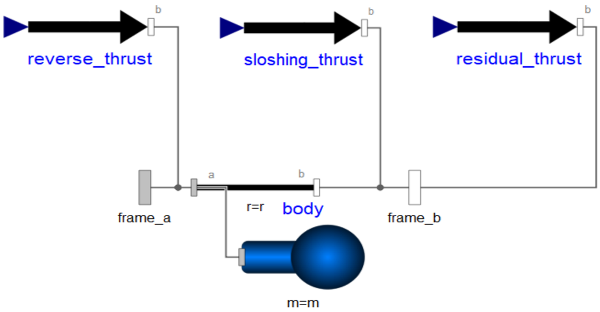


Figure 2: Schematic diagram of the first stage model

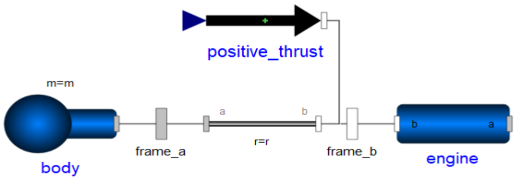


Figure 3: Schematic diagram of the second stage model

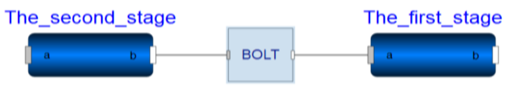


Figure 4: Schematic diagram of launch vehicle simulation model

Reverse thrust, sloshing force and positive thrust are regarded as constant forces. However, residual thrust exhibits variability over time. This study utilizes an interpolation function to model the residual thrust. The sensitivity index of residual thrust can be determined as follows

$$F_C = F_{C\min} + C(F_{C\max} - F_{C\min}) \quad (15)$$

where C represents the residual thrust coefficient; $F_{C\max}$ and $F_{C\min}$ represent the maximum and minimum residual thrust curves in Figure 5. By varying the value of coefficient C, the effect of residual thrust on the model can be examined.

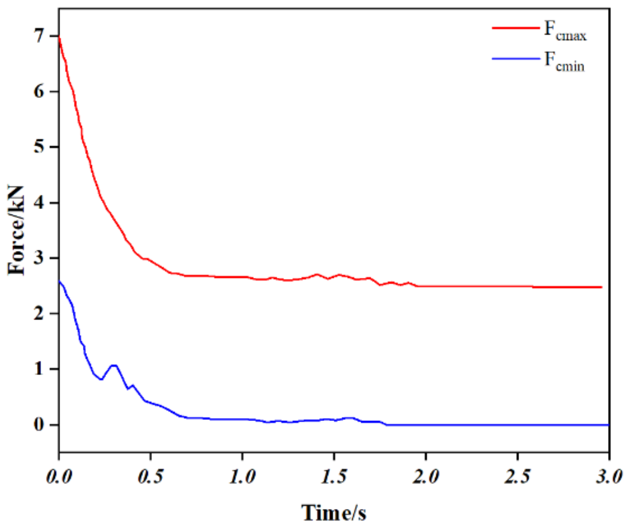


Figure 5: Time history curve of residual thrust

The most critical factor in evaluating the safe separation of launch vehicle stages is the minimum clearance between the first and second stages during the stage separation process [30]. This clearance is defined as the distance between the cylindrical nozzle of the second stage and the tube wall of the first stage. To calculate this minimum clearance, this study uses the Flexible Collision Library (FCL) [31]. The FCL is a collision detection library that offers a comprehensive framework for various collision detection models, including rigid body models, variable models, link class models, and point cloud representations. The FCL utilizes parameters such as position, angle, bounding box dimensions, and surface grids to effectively detect collisions between two objects. This paper focuses on the distance calculation function provided by the FCL library. The algorithm can be directly invoked within the proposed model. Using the calculated positional information as parameters, the minimum clearance in launch vehicle stage separation systems can be accurately determined.

After the completion of model creation, it is imperative to select parameters for the execution of Sobol sensitivity analysis. The parameters employed in the sensitivity analysis, along with their corresponding variation ranges, are outlined in Table 1. This study uses the Sobol sequence sampling method [32]. For each parameter, a total of 5000 random samples are generated for computational purposes.

Table 1: Parameters for launch vehicle stage separation

Parameters	Range
reverse thrust (one rocket)/ N, F_r	[21000, 22000]
positive thrust (one rocket)/ N, F_p	[2100, 2300]
axial offset of the center of mass of the first-stage rocket along the x-axis/ m, $\triangle x_1$	[-0.1, 0.1]
circumferential offset of the center of mass of the first-stage rocket along the y-axis/ m, $\triangle y_1$	[-0.05, 0.05]
circumferential offset of the center of mass of the first stage rocket along the z-axis/ m, $\triangle z_1$	[-0.05, 0.05]
axial offset of the center of mass of the second-stage rocket along the x-axis/ m, $\triangle x_2$	[-0.1, 0.1]
circumferential offset of the center of mass of the second-stage rocket along the y-axis/ m, $\triangle y_2$	[-0.05, 0.05]
circumferential offset of the center of mass of the second-stage rocket along the z-axis/ m, $\triangle z_2$	[-0.05, 0.05]
mass of the first stage/ kg, m_1	[25500,25600]
mass of the second stage/ kg, m_2	[59500,60500]
sloshing force in the y-axis/ N, F_{sy}	[-50,50]
sloshing force in the z-axis/ N, F_{sz}	[-50,50]
residual thrust coefficient, C	[0,1]

4.2 Analysis of Results

Figure 6 illustrates the impact of various parameters on the displacement of the first stage. As depicted in Figure 6 (a), residual thrust exerts the most significant influence on the axial displacement of the first stage, followed by the reverse thrust. In Figure 6 (b), it is evident that the global sensitivity index for offsets of the mass center in both the x and y

directions is considerably larger than that of the first-order sensitivity index. This suggests that the interaction between these two parameters plays a crucial role in affecting circumferential displacement in the y-direction for the first-stage. Similarly, as shown in Figure 6 (c), this interaction between mass center offsets in both x and y directions remains a critical factor influencing circumferential displacement in the z-direction for the first-stage.

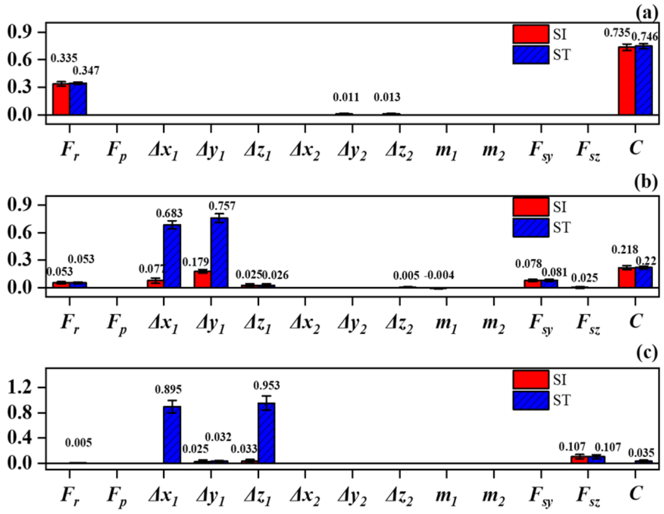


Figure 6: Influence of parameters on the first-stage displacements in axial *x* (a), circumferential y (b), and circumferential *z* directions (c)

Figure 7 shows the influence of various parameters on the displacement of the second stage. As shown in Figure 7 (a), the residual thrust exerts the most significant influence on the axial displacement in the x-direction for the second stage. In Figure 7 (b), it is evident that the offset of mass center in the y-direction from the first stage has a critical effect on circumferential displacement in the y-direction. Furthermore, Figure 7 (c) indicates that the offset of mass center in the *z*-direction from the first stage has a pronounced effect on circumferential displacement in that same *z*-direction.

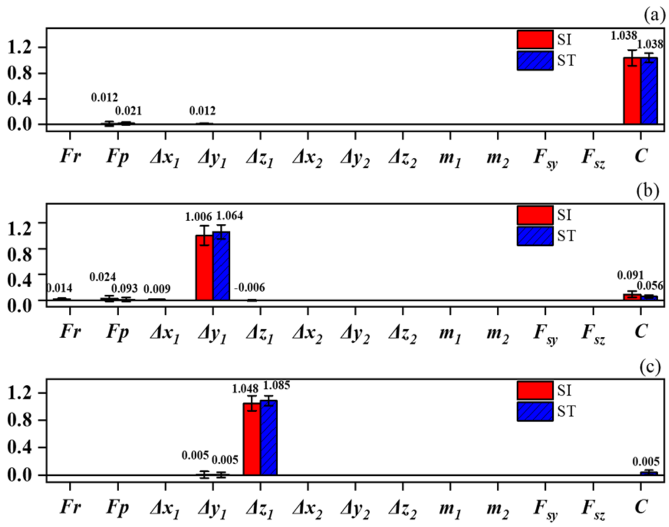


Figure 7: Influence of parameters on the second-stage displacements in axial *x* (a) and circumferential *y*, *z* directions (b, c)

Figure 8 shows the influence of parameters on the attitude angles of the first stage. As demonstrated in Figure 8 (a), the residual thrust exerts the most significant influence on the roll angle of the first stage. In Figure 8 (b), it is evident that the offset of mass center in the *z*-direction has a critical effect on the yaw angle. Furthermore, Figure 8 (c) reveals that the offset of mass center in the y-direction has a predominant impact on the pitch angle.

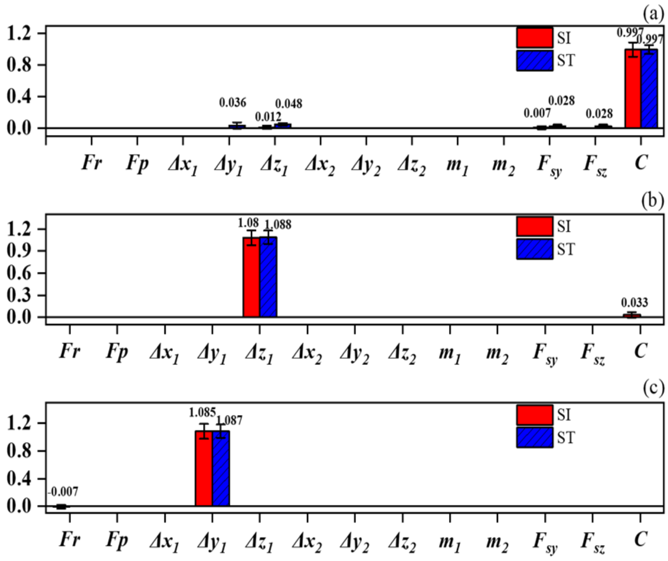


Figure 8: Influence of parameters on the first-stage roll (a), pitch (b), and yaw angles (c)

Figure 9 shows the influence of parameters on the attitude angles of the second stage. As demonstrated in Figure 9 (a), residual thrust exerts the most significant influence on the roll angle of the second stage. Figure 9 (b) indicates that the offset of mass center in the *z*-direction of the first stage has a pronounced effect on the yaw angle. Additionally, Figure 9 (c) indicates that the offset of mass center in the *y*-direction of the first stage has a substantial impact on pitch angle.

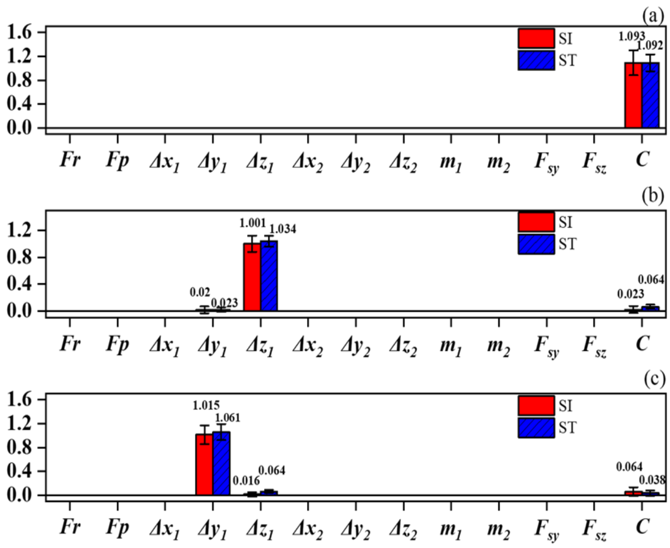


Figure 9: Influence of parameters on the second-stage roll (a), pitch (b), and yaw angles (c)

Figure 10 shows the influence of parameters on the minimum clearance. It illustrates that the residual thrust has the most substantial influence on the minimum clearance between the two stages.

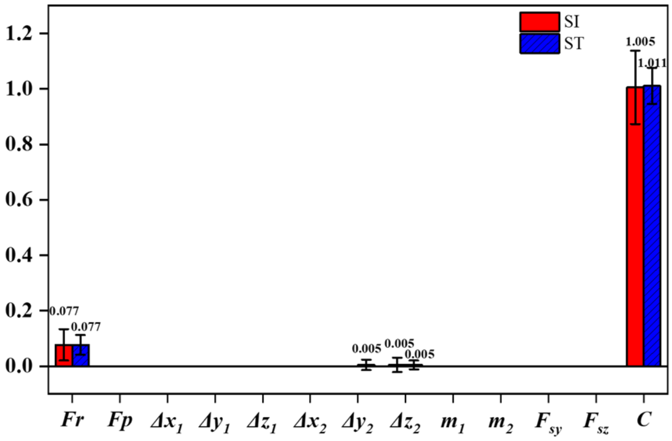


Figure 10: Influence of parameters on the minimum clearance

5. Conclusion Remarks

Based on the stage separation model of launch vehicles developed in MWorks, this paper utilizes the Sobol method to conduct a global sensitivity analysis. This analysis examines the effects of various separation parameters, including reverse thrust, positive thrust, residual thrust, sloshing force, mass characteristics, and the offsets of the center of mass for both the first and second stages. The analysis focuses on the effects of these parameters on displacement, attitude control, and the minimum clearance between the two stages. The simulation results indicate that residual thrust is a critical factor affecting axial displacement, roll angle, and the minimum clearance during stage separation. Furthermore, the interactions between axial and circumferential offset of the center of mass significantly impact circumferential displacement in the first stage. Specifically, the offset in the y-direction has a significant impact on both y-direction displacement in the second stage and the pitch angles across both stages. Similarly, the offset in the z-direction predominantly impacts z-direction displacement in the second stage as well as yaw angles for both stages. Therefore, future optimization designs aimed at controlling displacement behaviour, ensuring attitude stability, and minimizing separation clearances during the stage separation of launch vehicles can be effectively achieved by regulating residual thrust and making adjustments to the center-of-mass offsets within these vehicles.

Acknowledgments

This paper was partially supported by the Fundamental Research Funds for the Central Universities (Grant 30923010927). It supports are greatly acknowledged and appreciated.

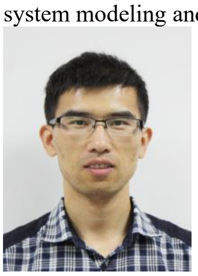
References

[1] Shi ZQ. Research on pressure and temperature testing technology for the stage separation of the launch vehicle (in Chinese). Dissertation. North University of China; 2015
[2] Luo PC, Fu PF. Summary of weapon equipment sensitivity analysis methods (in Chinese). Computer Engineering and Design. 2008; (21): 5546-5549.
[3] Sanio D, Ahrens M A, Mark P. Lifetime predictions of prestressed concrete bridges—Evaluating parameters of relevance using Sobol' indices. Civil Engineering Design, 2021; 4(5-6).
[4] Lai X, Meng Z, Wang SY, et al. Global parametric sensitivity analysis of equivalent circuit model based on Sobol' method for lithium-ion batteries in electric vehicles. Journal of Cleaner Production. 2021; 294.
[5] Pan X, Zhang ZY, Zhang YM, Wang RR. Effectiveness evaluation of equipment system support based on Sobol sensitivity analysis (in Chinese). Journal of Systems Engineering and Electronics. 2021; 43(02): 390-398.
[6] Cao XQ, Su SP, Leng HZ, Liu BN. Global Sensitivity Analysis of Parameters in the ENSO model Based on Sobol' Method. Journal of Coastal Research. 2020; 99(sp1).
[7] Kumar D, Singh A, Kumar P, et al. Sobol sensitivity analysis for risk assessment of uranium in groundwater. Environmental geochemistry and health. 2020; 42(6).
[8] Le Guyadec M, Gerbaud L, Vinot E, Delinchant B. Sensitivity analysis using Sobol indices for the thermal modelling of an electrical machine for sizing by optimization. Compel. 2019; 38(3).
[9] Zhou B, Wang L, Liu Y, Hu Y. Analysis of factor sensitivity in brake friction and wear performance based on the Sobol method. Journal of the Brazilian Society of Mechanical Sciences and Engineering. 2018; 40(7).
[10] Xu JF, Yang G, Jiang SH, Wu L. Sensitivity analysis of the combat effectiveness of air defence of warship based on Sobol index method (in Chinese). Journal of Ordnance Equipment Engineering. 2023; 44(07): 189-196.
[11] Ortega Pelayo RE, El Bouzidi S, Trottier A, Forgues F, Pfeiffer S. Structural integrity assessment of CANDU pressure tubes using Sobol indices for global sensitivity analysis. Nuclear Engineering and Design. 2024; 428: 113499.
[12] Mao ZJ, Luo Y, Zhou SQ, Jin WY, Feng WP. The multi-objective optimisation design of outlet guide vanes of diagonal flow fan based on Sobol sensitivity analysis. Proceedings of the Institution of Mechanical Engineers, Part A: Journal of Power and Energy. 2024; 238(3): 382-400.
[13] Zhang M, Liu CL, Hu RC, Han H, Wu QW. Comparing global sensitivity analysis methods for the joint thermal design parameters of a space manipulator based on the Sobol' and PAWN. Thermal Science and Engineering Progress. 2024; 47: 102338.
[14] Fuat K, Ertekin B. Sobol sensitivity analysis and acoustic solid coupling approach to underwater explosion. Ocean Engineering. 2023; 281.
[15] Wang ZH, Li MX, Ren FS, et al. Sobol sensitivity analysis and multi-objective optimization of manifold microchannel heat sink considering entropy generation minimization. International Journal of Heat and Mass Transfer. 2023; 208.
[16] Liang LH, Li CH, Wang LN, et al. Sensitivity analysis of heat transfer coefficient in primary system for LMSR core power control system based on Sobol's method. Annals of Nuclear Energy. 2023; 180.
[17] Han JH, Wang LP, Ma FJ, et al. Sensitivity analysis of geometric error for a novel slide grinder based on improved Sobol method and its application. The International Journal of Advanced Manufacturing Technology. 2022; 121(9-10): 6661-6684.

[18] Tahmasbi V, Ghoreishi M, Zolfaghari M. Sensitivity analysis of temperature and force in robotic bone drilling process using Sobol statistical method. Biotechnology & Biotechnological Equipment; 2018; 32(1): 130-141.
[19] Xu K, Zheng CJ, Yu ZQ, et al. Sensitivity analysis of nozzle parameters of solid rocket motors based on Sobol method (in Chinese). Journal of Solid Rocket Technology. 2022; 45(06): 830-837.
[20] Cheng W. Uncertainty analysis of flight mechanics parameters of aircraft based on chaos polynomial expansion (in Chinese). Dissertation. Hunan University; 2021.
[21] Wang Q, Li HY, Lu L, Yang LY, Wang SQ. Global Sensitivity Analysis of Earth-Moon Transfer Orbit Parameters Based on Sobol Method. International Journal of Aerospace Engineering. 2022; 2022
[22] Song J, She, Hu Q, Li C, Cai Q. Multi-objective constrained optimization of rocket self-propelled ejection based on Sobol sensitivity analysis (in Chinese). Journal of Propulsion Technology. 2022; 43(12): 45-53.
[23] Liu B. Uncertainty quantification method for aircraft guidance and control system (in Chinese). Dissertation. Harbin Institute of Technology; 2019
[24] Wang SX, Song Y, Wang YH, Niu WD, Lei Z. Sensitivity analysis of energy consumption parameters of Petrel-II underwater glider based on Sobol method (in Chinese). Journal of Tianjin University (Science and Technology). 2017; 50(02): 113-120.
[25] Yin JJ, Chang F, Li SL, Yang Z, Shi XP. Sensitivity analysis of damage tolerance design parameters of integral wing beam based on Sobol method(in Chinese). Journal of Air Force Engineering University (Natural Science Edition). 2013; 14(06): 9-12.
[26] Zhang DY, Zhu ZX, Zhang HL. Design of AGV Chassis Motion Control System Based on MWorks. Journal of Physics: Conference Series. 2023; 2479(1).
[27] Sobol I M. Sensitivity estimates for nonlinear mathematical models. Math.model.comput.exp. 1993; 1(1): 112, 118
[28] Zhang XH. Research on global sensitivity analysis method of operational effectiveness of air defense missile weapon equipment system (in Chinese). Dissertation. National University of Defense Technology; 2010.
[29] Zhang WF, Cai XS, Liu ZD, Liu X, Tong YF. Parameterized Modelling of Stage Separation of Launch Vehicles with Modelica. Proceedings of the 2nd International Conference on Mechanical System Dynamics; Beijing, China, 2023.
[30] 30, Yue BZ, Hao BL, et al. Stage separation of recoverable liquid launch vehicle by using moving pulsating ball analogue for propellant sloshing. Chinese Journal of Aeronautics. 2024; 37(2): 360-370.
[31] Pan J, Chitta S, Manocha D. FCL: A General Purpose Library for Collision and Proximity Queries. Proc. of the IEEE International Conference on Robotics and Automation (ICRA). St. Paul, Minnesota, USA, 2012.
[32] Zhang YC, Wang LL. Reliability analysis of inclined cables based on Sobol sequence sampling. Western China Communication Science & Technology. 2022; (8): 111-114.

Author Profile

Haoqi Zhang is currently pursuing a master degree in multi-body system dynamics at the School of Physics, Nanjing University of Science and Technology. His research interests include complex system modeling and simulation as well as separation.



Qingtao Wang received his B.Sc., M.Sc. and Ph.D. degrees from Nanjing University of Aeronautics and Astronautics, China, in 2008, 2010 and 2016, respectively. He is a currently associate professor at Department of Mechanics and Engineering Sciences, Nanjing University of Science and Technology. His research interests include multibody system dynamics, space tether transportation system, spacecraft dynamics and satellites separation dynamics.

Yifan Tong is currently working toward the master degree in multi-body system dynamics in School of Physics, Nanjing University of Science and Technology. His research interests include space dynamics and separation dynamics.