

A Unified Parametric Modeling Method for Conventional, Semi-Buried, and Embedded Inlets

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Abstract

To address the issue that current missile inlet design studies mainly focus on individual configurations and lack a unified parametric modeling method capable of representing different inlet types, this paper investigates three inlet configurations: conventional inlets, semi-buried inlets, and embedded inlets. The geometric characteristics and design procedures of these three inlet types are systematically analyzed, and a unified parametric modeling method applicable to different inlet layout configurations is established. By adopting consistent parameter definitions and mathematical descriptions, the proposed method enables the rapid generation and configuration transformation of geometric models for conventional, semi-buried, and embedded inlets. Geometric modeling validations are conducted for different inlet configurations based on the developed model. The results show that the proposed method can effectively represent the main geometric characteristics of all three inlet types while demonstrating good versatility and modeling efficiency. This method provides a unified geometric modeling foundation for the aerodynamic design, optimization analysis, and rapid performance evaluation of missile inlets.

Keywords: S-shaped inlet; missile inlet;unified parametric modeling; geometric modeling

1. Introduction

The inlet is a critical component of an aircraft propulsion system, responsible for capturing, compressing, and conditioning the incoming airflow before it enters the engine. Its primary function is not only to provide a sufficient mass flow rate of air but also to ensure high-quality inlet flow conditions. Therefore, the design characteristics and operating performance of the inlet have a direct impact on engine performance and consequently influence the overall aerodynamic performance of the flight vehicle.

With the development of highly maneuverable, low-observable, and highly integrated flight vehicles, inlet configurations have become increasingly diverse. Depending on vehicle layout and stealth requirements, missile inlets can generally be classified into conventional inlets, semi-buried inlets, and fully buried inlets. Conventional inlets are characterized by their simple structure and high flow efficiency. Semi-buried inlets provide a balance between aerodynamic and stealth performance, whereas fully buried inlets are widely employed in advanced flight vehicles due to their superior radar stealth characteristics. Extensive research has been conducted on the aerodynamic characteristics, flow-field optimization, and aerodynamic–stealth integrated design of various inlet configurations, resulting in significant advances in the field.

Huang et al. [1] reviewed the recent research progress on two types of subsonic serpentine inlets, namely ultra-compact S-duct inlets and boundary-layer-ingesting inlets. Their study indicated that current CFD methods still exhibit considerable discrepancies in predicting total-pressure distortion, highlighting an important direction for future investigations. Wang et al. [2] employed CFD simulations to investigate the effects of geometric parameters, including the offset distance and duct length of an S-shaped inlet, on total-pressure recovery and outlet distortion. The results demonstrated that an appropriate increase in offset distance is beneficial for reducing total-pressure distortion, while

increasing duct length can improve total-pressure recovery and alleviate outlet flow distortion. Li et al. [3] studied the influence of shape indices during cross-sectional transitions on the aerodynamic performance of S-shaped inlets and proposed an improved super-ellipse design method that establishes a relationship between the shape index and the cross-sectional area variation. Li et al. [4] summarized a design methodology suitable for missile applications by adjusting parameters such as the centerline profile, area distribution, lip geometry, and throat location, enabling the design of large-offset, short-diffuser S-shaped inlets. Zhang et al. [5] conducted aerodynamic optimization studies of S-shaped inlets and proposed an innovative overflow-hole-based flow-control technique, which effectively improved the aerodynamic characteristics at the inlet exit. Sun et al. [6] investigated the internal flow structures and performance characteristics of a flush-mounted buried side inlet. Through CFD analyses, the effects of freestream Mach number, angle of attack, sideslip angle, and exit Mach number on inlet performance and flow structures were examined, and approaches for aerodynamic performance enhancement were discussed. Jia et al. [7] studied S-shaped inlets for distributed propulsion systems and analyzed the influence of key geometric parameters, including centerline offset distance and inlet aspect ratio, on aerodynamic performance.

In addition to conventional and fully buried S-shaped inlets, Liu et al. [8] investigated the outlet distortion characteristics of a semi-buried S-shaped inlet. Using the Isight optimization platform combined with a Non-dominated Sorting Genetic Algorithm (NSGA), the diffuser section was optimized, resulting in significant improvements in aerodynamic performance. Lu et al. [9] analyzed the effects of geometric parameters on the aerodynamic characteristics of a two-dimensional mixed-compression supersonic inlet. The relationships among these parameters were summarized and mathematical models were established, providing an exploratory approach for inlet modeling and laying the foundation for further research on integrated propulsion-system control.

Although extensive studies have been conducted on the aerodynamic design and optimization of individual inlet configurations, existing research is generally limited to specific inlet types and lacks a unified parameterization framework capable of describing multiple inlet configurations. Consequently, when different inlet layouts are considered during conceptual design and multidisciplinary optimization, separate geometric models and parameter systems must often be established, resulting in reduced design efficiency and poor model reusability. Therefore, the development of a unified parametric modeling methodology applicable to conventional, semi-buried, and fully buried inlets is of considerable importance for rapid design, aerodynamic–stealth integrated optimization, and performance evaluation of missile inlet systems.

However, existing studies have primarily focused on the design and optimization of specific inlet configurations, and a unified geometric description and parameter system applicable to different inlet types is still lacking. As a result, when conducting multi-configuration comparisons, configuration transformations, or aerodynamic optimization, separate geometric models must typically be developed for each inlet type. This not only increases the design workload but also limits the reuse of design knowledge and modeling methodologies. Therefore, the development of a unified parametric modeling approach capable of describing conventional, semi-buried, and embedded inlets is of significant importance for improving design efficiency, supporting rapid performance evaluation, and enabling intelligent optimization.

To address these challenges, this paper investigates three types of missile inlets: conventional inlets, semi-buried inlets, and embedded inlets. Based on a systematic analysis of the geometric characteristics and traditional design methodologies of the three inlet configurations, the key design parameters governing inlet geometry are identified, and a unified parametric modeling method is established. By employing consistent parameter definitions and mathematical descriptions, the proposed method enables rapid generation and configuration transformation of different inlet geometries. The effectiveness and applicability of the proposed approach are demonstrated through modeling studies of representative inlet configurations. The developed methodology provides a unified geometric modeling foundation for rapid inlet design, aerodynamic optimization, and performance prediction of missile inlet systems.

2. Design Methodologies for Three Types of Inlets

For S-shaped inlets, the centerline profile and cross-sectional area distribution are the primary factors governing the aerodynamic design[10]. The centerline profile determines the flow-turning process within the duct. As the airflow passes through the curved passage, centrifugal forces generate non-uniform pressure distributions and induce secondary flows, which can significantly increase flow distortion. Therefore, the centerline profile directly influences the transverse pressure gradients and the resulting secondary-flow structures within the inlet. The cross-sectional area distribution governs the streamwise diffusion process. An excessive local diffusion rate may lead to boundary-layer separation, resulting in a substantial deterioration of inlet performance.

Regardless of whether the inlet configuration is conventional, semi-buried, or embedded, both the centerline profile and the area distribution must be carefully designed. In current engineering practice, three typical loading types are commonly used to describe the centerline curvature and area variation: fore-loaded, uniformly loaded, and aft-loaded profiles. These loading types correspond to cases in which the majority of the flow turning or area diffusion occurs in the upstream, middle, and downstream portions of the duct, respectively.

The centerline profile can be expressed using a fourth-order polynomial:

$$Y = \Delta Y\left[A\left(\frac{X}{L}\right)^2 + B\left(\frac{X}{L}\right)^3 + C\left(\frac{X}{L}\right)^4\right] \tag{1}$$

where Δy is the total offset distance of the inlet centerline, L is the duct length, and X and Y denote the axial and transverse coordinates of the centerline, respectively. The coefficients A, B, and C are shape-control parameters with typical ranges of A∈[0，6],B∈[-8，4],C∈[-3，3].

By adjusting these parameters, different curvature distributions and turning-load distributions can be achieved. When the majority of the flow turning occurs in the upstream section of the duct, the profile is referred to as a fore-loaded profile. When the turning is distributed evenly along the duct, it is referred to as a uniformly distributed profile. Conversely, when the turning is concentrated in the downstream section, the profile is classified as an aft-loaded profile. Different loading distributions result in different transverse pressure gradients and secondary-flow structures, thereby affecting total-pressure recovery and flow distortion at the inlet exit.

The cross-sectional area distribution is expressed as:

$$\frac{A}{A_1} = \left(\frac{A_2}{A_1} - 1\right)\left[D\left(\frac{X}{L}\right)^2 + E\left(\frac{X}{L}\right)^3 + F\left(\frac{X}{L}\right)^4\right] + 1 \tag{2}$$

where A_1 and A_2 are the inlet and exit cross-sectional areas, respectively, A_2 / A_1 represents the overall area ratio, and A denotes the local cross-sectional area along the duct. The coefficients D, E, and F are area-distribution control parameters with typical ranges of D∈[0，6],E∈[-8，4],F∈[-3，3].

By varying these coefficients, different diffusion-load distributions can be generated. A fore-loaded area distribution concentrates most of the diffusion in the upstream portion of the duct, whereas an aft-loaded distribution delays the diffusion process to the downstream region. A uniformly distributed profile provides a relatively even diffusion rate throughout the duct. Since excessive local diffusion may induce boundary-layer separation and degrade aerodynamic performance, the selection of an appropriate area-distribution profile is critical to achieving satisfactory inlet performance.

2.1 Conventional Inlet Configuration

Since the entrance of a conventional inlet is directly exposed to the freestream, its cross-sectional shape significantly affects the capture area, flow distortion level, boundary-layer interaction characteristics, and flow stability under sideslip conditions. Therefore, in addition to the

parameterization of the duct centerline and cross-sectional area distribution, an accurate geometric description and parameterization of the inlet cross-section are also essential.

In this study, an elliptical inlet cross-section is adopted as the baseline cross-sectional configuration for the conventional inlet. The elliptical cross-section is defined by its major and minor axes, with characteristic dimensions of 2a and 2b, respectively. At the inlet, the major axis 2a is assigned a prescribed value. To improve inlet performance under sideslip conditions and enhance lateral flow adaptability, this value is typically designed to be larger than the outlet diameter. The major axis then gradually contracts along the streamwise direction according to a prescribed width-contraction angle until it matches the outlet diameter. The minor axis 2b is determined at the inlet based on a specified aspect ratio and varies continuously according to a predefined function. Eventually, both axes converge at the outlet to form a complete circular cross-section.

By defining the duct centerline, the streamwise variation of cross-sectional area, and the elliptical cross-sectional shape parameters, the three-dimensional internal geometry of the conventional inlet can be fully determined. Specifically, the centerline determines the spatial trajectory of the duct, the cross-sectional area distribution governs the contraction and diffusion characteristics, and the elliptical shape parameters define the detailed geometry of each section. The parameter definitions and geometric schematic of the elliptical inlet cross-section are shown in Fig. 1.

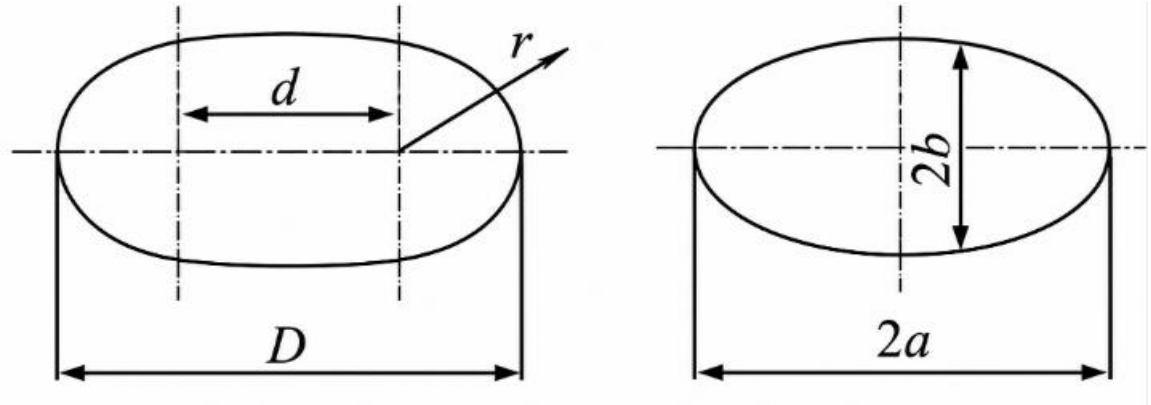


Figure 1 - Common Inlet Cross-Sectional Shapes

In this study, an elliptical inlet cross-section is adopted as the inlet geometric configuration of the duct. By defining the duct centerline, the streamwise variation of cross-sectional area, and the cross-sectional shape parameters, the three-dimensional internal geometry of a conventional inlet duct can be fully described.

2.2 Semi-Buried Inlet Configuration

For semi-buried inlets, the parameterization of the internal duct geometry can be established as an extension of the conventional inlet modeling approach. Since the inlet section is partially embedded in the missile or fuselage surface, the internal geometry can be fully defined by modifying the inlet cross-sectional shape and the cross-sectional transition method, while the duct centerline and cross-sectional area distribution can still follow the parameterization used for conventional inlets.

For the inlet cross-section, a partial elliptical configuration is adopted for the semi-buried inlet. Specifically, only the lower half of the ellipse with respect to the major axis is retained, with the major-axis boundary directly attached to the external body surface, thereby forming a flush-mounted inlet geometry. This configuration effectively represents the geometric coupling between the semi-buried inlet and the vehicle surface.

For the cross-sectional transition, a smooth transformation from the inlet shape to the downstream circular outlet is required. To achieve this, the geometry of the upper boundary is parameterized using an interpolation transition function. At the inlet, the upper boundary is represented by a straight edge aligned with the major axis. Along the streamwise direction, this boundary gradually expands outward according to a prescribed interpolation law, evolving into a smooth curve with continuous geometric variation and eventually forming the upper half of a complete ellipse. By adjusting the interpolation function and its associated parameters, the transition rate and curvature distribution can be flexibly controlled, allowing the geometric design requirements of different semi-

buried inlet configurations to be satisfied.

2.3 Embedded Inlet Configuration

Compared with conventional and semi-buried inlets, embedded inlets exhibit more distinctive inlet geometric characteristics. The inlet cross-section lies on the horizontal plane of the missile body and is therefore no longer perpendicular to the duct centerline. Instead, it forms a finite angle with the centerline. In addition, from an aerodynamic design perspective, a nonzero inlet tangent slope of the duct centerline is generally required to ensure sufficient intake efficiency and to avoid severe flow separation near the inlet. Therefore, during the parameterization process, the inlet inclination angle of the centerline, denoted by θ must first be specified to define the spatial orientation of the inlet section.

For the construction of the inlet cross-section, the actual inlet geometry can be derived from the cross-section defined at the starting point of the duct centerline. Specifically, the cross-section at the centerline origin is rotated about the local -y axis by an angle of ($90^\circ - \theta$), thereby generating the inlet cross-section that satisfies the required installation orientation. This approach ensures a clear geometric relationship between the inlet cross-section and the internal duct sections, while accurately capturing the relative position between the embedded inlet and the missile body surface.

The streamwise variation of the cross-sectional area in the embedded inlet follows the same parameterization approach as that used for the conventional inlet. Specifically, the cross-sectional area contracts or expands along the duct according to a prescribed function and ultimately converges to a circular outlet section. However, because an initial angle exists between the inlet cross-section and the internal normal-plane cross-section, an additional transition in sectional orientation must be considered during geometry generation. To address this, an interpolation transition function is introduced to control the angular variation between the generated sectional plane and the normal plane of the centerline. At the inlet, this angle is equal to ($90^\circ - \theta$) and it gradually decreases along the streamwise direction according to a prescribed interpolation law until it converges to 0° at the outlet, where the generated section fully coincides with the normal-plane cross-section.

3. Unified Parametric Design MethodStyle of Writing

Abbreviations should be spelt out in full the first time they appear and their abbreviated form included in brackets immediately after. Words used in a special context should appear between single quotation marks the first time they appear.

Based on the design methodologies of the three inlet configurations described above, their common and distinct geometric characteristics can be summarized to establish a unified parametric modeling framework. Fundamentally, all three inlet types can be described using a common set of geometric elements, including the duct centerline, streamwise cross-sectional area distribution, cross-sectional shape, and sectional orientation transition. Therefore, a unified parameterization framework can be constructed to represent inlet configurations with different installation layouts.

The primary differences among the three inlet types lie in the inlet cross-sectional configuration and the transition of sectional orientation. To distinguish different inlet configurations, three discrete control variables, K_1, K_2, and K_3, are introduced to represent the conventional inlet, semi-buried inlet, and embedded inlet, respectively. By controlling the values of these variables, different inlet configurations can be selected within the unified parametric model.

Specifically, when $(K_1,K_2,K_3)=(1,0,0)$ meaning only $K_1=1$, the model represents a conventional inlet. When $(K_1,K_2,K_3)=(0,1,0)$ meaning only $K_2=1$ the model represents a semi-buried inlet. When $(K_1,K_2,K_3)=(0,0,1)$ meaning only $K_3=1$, the model represents an embedded inlet. Since only one inlet type can be activated at a time, these three control variables must satisfy a mutually exclusive constraint, which can be expressed as follows:

$$\begin{aligned} K_1 + K_2 + K_3 &= 1 \\ K &\in \{0,1\} \end{aligned} \tag{3}$$

3.1 Unified Design of the Centerline

Since the tangent slope of the centerline at the inlet is generally zero for a conventional inlet, directly applying this centerline formulation to an embedded inlet may reduce the flow-capture capability near the inlet and adversely affect the intake efficiency. Therefore, based on the original centerline shape function, a linear-term coefficient is further introduced in this study to control the inlet tangent slope of the centerline, thereby improving the geometric adaptability of the inlet region for embedded inlet configurations.

Since this inlet tangent-slope correction is a geometric feature unique to the embedded inlet, the linear term is activated only for the embedded inlet configuration. To this end, the control variable K3 is introduced as the switching coefficient of the correction term. When K3=1 the current configuration corresponds to an embedded inlet, and the linear term is included in the centerline shape function. When K3=0 the linear term is deactivated, and the centerline expression degenerates into the form used for conventional or semi-buried inlets. In this way, different centerline formulations can be switched within the unified parametric framework.

The centerline shape function can be expressed as follows:

$$f\left(\xi\right)=K_3 p\xi+A\xi^2+B\xi^3+C\xi^4 \tag{4}$$

$$\xi=\frac{x}{L} \tag{5}$$

Here, ξ denotes the nondimensional axial coordinate obtained by normalizing the axial coordinate x with the inlet length L. For the convenience of subsequent parameterization and unified description of different configurations, all geometric variables and design parameters in this study are expressed in nondimensional form.

After introducing the linear-term coefficient p into the centerline shape function, with K3 serving as its control coefficient, this linear term is activated only when K3≠0 Since K3 corresponds exclusively to the embedded inlet configuration, only the embedded inlet exhibits a nonzero tangent slope at the centerline inlet. For conventional and semi-buried inlets, K3=0, and the inlet tangent slope remains zero.Therefore, the corresponding parameters in the centerline shape function must satisfy the following constraint:

$$f'\left(\xi\right)=K_3 p+2A\xi+3B\xi^2+4C\xi^3 \tag{6}$$

$$f\left(0\right)=0,\quad f\left(1\right)=1,\quad f'\left(1\right)=0 \tag{7}$$

$$\begin{cases} p+2A+3B+4C=1 \\ p+A+B+C=1 \end{cases} \tag{8}$$

$$\frac{dZ}{dx}=\frac{\Delta Z}{L}f'\left(\xi\right) \tag{9}$$

For the centerline offset, the starting point of the centerline for both the semi-buried inlet and the embedded inlet is located near the lower surface of the missile body. In contrast, when the configuration is switched to the conventional inlet, an additional offset must be introduced on the original basis to avoid geometric interference between the inlet section and the external body surface. This offset accounts for the inlet installation clearance h and the minor semi-axis b of the elliptical inlet section. Therefore, the configuration control variable K1 is also introduced to distinguish the difference in the centerline starting position between the conventional inlet and the other two inlet configurations. The total centerline offset in the Z-direction can therefore be expressed as

$$\Delta Z=\Delta Z_1+K_1\left(h+b\right) \tag{10}$$

As indicated by this expression, when K_1=0 the offset corresponds to that of the semi-buried or embedded inlet. When K_1=1 the additional inlet installation clearance and the offset associated with

the inlet minor semi-axis are included, yielding the centerline offset for the conventional inlet. Since the centerline offset exists only in the Z-direction and no offset is introduced in the Y-direction, the complete spatial expression of the centerline can be determined by further incorporating the inlet inclination angle θ.

The centerline offset is introduced only in the Z-direction, while no lateral offset is applied in the Y-direction. Therefore, by incorporating the previously defined centerline shape function, the Z-direction offset ΔZ and the inlet inclination angle θ the complete spatial expression of the inlet centerline can be determined.

$$\begin{cases} X\left(x\right)=x_0+x \\ Y\left(x\right)=y_0 \\ Z\left(x\right)=z_0+\Delta Z\cdot f\left(\xi\right)=z_0+\Delta Z\cdot\left(K_3p\xi+A\xi^2+B\xi^3+C\xi^4\right) \\ =z_0+\left(\Delta Z_1+K_1\left(h+b\right)\right)\left(K_3p\xi+A\xi^2+B\xi^3+C\xi^4\right) \end{cases} \tag{11}$$

$$\theta=\arctan\left(\frac{K_3p\cdot\Delta Z}{L}\right) \tag{12}$$

3.2 Cross-Sectional Area Distribution

By nondimensionalizing the original cross-sectional area variation law, the unified area distribution can be expressed as：

$$\frac{A}{A_1}=\left(\frac{A_2}{A_1}-1\right)\left[D\xi^2+E\xi^3+F\xi^4\right]+1 \tag{13}$$

Which is equivalently written as：

$$A(\xi)=A_1+\left(A_2-A_1\right)\sigma(\xi) \tag{14}$$

$$\sigma(\xi)=D\xi^2+E\xi^3+F\xi^4 \tag{15}$$

To ensure that the prescribed boundary conditions at the inlet and outlet are satisfied, the shape function must meet the following constraints:

$$\begin{aligned} &\sigma(0)=0,\quad A(0)=A_1 \\ &\sigma(1)=1,\quad A(L)=A_2 \end{aligned} \tag{16}$$

Accordingly, the coefficients D, E, and F must satisfy

$$\mathrm{D+E+F=1} \tag{17}$$

For the inlet area A_1, when the configuration corresponds to a semi-buried inlet, only the lower half of the original elliptical inlet section is retained. Therefore, the effective inlet area is half of that of the complete elliptical section used in the conventional inlet. To describe this difference within the unified parameterization framework, the control variable K_2 is introduced to modify the inlet area, enabling a unified definition of A1 for the conventional, semi-buried, and embedded inlet configurations.

$$A_1=\pi ab\left(1-\frac{K_2}{2}\right) \tag{18}$$

For the variation of the major and minor axes of the elliptical cross-section, a width contraction angle is prescribed along the major-axis direction to determine the streamwise variation of the major semi-axis. Once the cross-sectional area and the major semi-axis are specified at each axial station, the corresponding minor semi-axis can be determined accordingly.

$$a(x)=a_{in}-x\tan\beta \tag{19}$$

$$b(x)=\frac{A(x)}{\pi a(x)} \tag{20}$$

When the inlet configuration is semi-buried, the front part of the duct has not yet recovered to a complete elliptical section. Therefore, a section-recovery factor is introduced to describe the gradual transition from the partial inlet section to a complete elliptical section. An interpolation transition function is employed for this purpose, and the axial location at which the section fully recovers to an ellipse is defined as the recovery position.

$$\begin{aligned}&\beta_s(x)=\left[1-\sigma_s\left(\frac{x}{x_{rec}}\right)\right], \quad x<x_{rec}\\&\beta_s(x)=0, \quad x\geq x_{rec}\\&\sigma_s(t)=3t^2-2t^3\end{aligned} \tag{21}$$

Accordingly, the variation of the minor semi-axis can be modified by considering the section-recovery factor. This treatment enables the effective area reduction caused by the partial elliptical section in the semi-buried inlet to be represented within the unified parameterization framework.

$$b(x)=\frac{A(x)}{\pi a(x)\left(1-\frac{K_2\beta_s(x)}{2}\right)} \tag{22}$$

Thus, for any given point along the duct centerline, once the major and minor semi-axes of the initial elliptical section are specified, the inlet area can be determined. Combined with the prescribed outlet area, the area distribution along the duct can then be obtained. The variation of the major semi-axis is governed by the width contraction angle, while the minor semi-axis is inferred from the cross-sectional area and the recovery correction. In this way, the geometric shape of the cross-section at each axial station can be determined.

3.3 Section Design Method for Embedded Inlets

In the previously defined cross-sectional area variation law, the resulting elliptical geometry is located on the normal plane of the duct centerline at each axial station. This treatment is applicable to conventional and semi-buried inlets. However, for the embedded inlet, whose entrance is located on the horizontal plane of the missile body and whose centerline has a nonzero inlet inclination angle, further modification is required.

For the embedded inlet, the inlet section is obtained by rotating the normal-plane cross-section at the starting point of the centerline about the local axis. At the outlet, the generated sectional plane coincides with the normal plane of the centerline, meaning that the included angle between the two planes becomes zero. Therefore, an interpolation transition function is introduced to define the sectional orientation factor, as given by

$$\eta(\xi)=K_3\left(1-\sigma(\xi)\right) \tag{23}$$

where the interpolation function and the corresponding boundary conditions are defined as：

$$\begin{aligned}&\sigma(\xi)=3\xi^2-2\xi^3\\&\eta(0)=K_3, \quad \eta(1)=0\end{aligned} \tag{24}$$

Accordingly, the included angle between the generated section and the normal plane of the centerline for the embedded inlet can be obtained as：

$$\psi(\xi) = \eta(\xi) \cdot \left(\frac{\pi}{2} - \theta \right) \tag{25}$$

To ensure that the elliptical geometry projected onto the normal plane satisfies the prescribed cross-sectional area distribution, the geometric parameters of the actually generated section must be corrected according to the included angle between the generated section and the normal plane of the centerline. Specifically, the actual sectional area can be inferred from the angle between the two planes and the target cross-sectional area, and this correction is further applied to the major and minor semi-axes of the ellipse. The relationship can be expressed as

$$A_{cap} = A_{act} \cdot \cos^2 \psi \tag{26}$$

$$a_{act}(x) = a_{cap}(x) \left[1 + K_3 \left(\frac{1}{\cos \psi(\xi)} - 1 \right) \right] \tag{27}$$

$$b_{act}(x) = b_{cap}(x) \left[1 + K_3 \left(\frac{1}{\cos \psi(\xi)} - 1 \right) \right] \tag{28}$$

where a_{act} , b_{act} , and A_{act} denote the major semi-axis, minor semi-axis, and area of the elliptical section in the actual generated coordinate plane of the embedded inlet, respectively. Similarly, a_{cap} , b_{cap} , and A_{cap} denote the major semi-axis, minor semi-axis, and area of the ellipse projected onto the normal plane corresponding to the duct centerline. Since the cross-sectional area distribution is defined on the normal plane of the centerline, A_{cap} represents the target cross-sectional area satisfying the prescribed area distribution, whereas A_{act} represents the actual generated sectional area after considering the sectional-orientation correction.

For the conventional and semi-buried inlet configurations K_3=0, and the correction term is automatically deactivated. In this case, the actual generated section remains identical to the section on the normal plane of the centerline. For the embedded inlet configuration, K_3=1, and both the major and minor semi-axes are corrected according to the sectional angle, ensuring that the projected section on the centerline normal plane still satisfies the prescribed cross-sectional area distribution. Through this treatment, the cross-sectional geometry generation process of conventional, semi-buried, and embedded inlets can be described within a unified parameterization framework.

3.4 Sectional Basis Vector Construction

For conventional and semi-buried inlets, the coordinate points generated from the major and minor semi-axes of the ellipse are directly located in the corresponding cross-sectional plane. For the embedded inlet, however, an included angle exists between the actually generated section and the normal plane of the centerline. Therefore, the elliptical dimensions on the actual section must be further inferred, and the coordinate points should be generated within this actual sectional plane. To construct the three-dimensional sectional points, a local coordinate system is established at each axial station along the centerline, and sectional basis vectors are introduced to map the two-dimensional sectional geometry into three-dimensional space.

The unit tangent vector of the centerline can be expressed as:

$$\hat{\mathbf{t}}(x) = \frac{\left(1, 0, \frac{dZ}{dx} \right)}{\sqrt{1 + \left(\frac{dZ}{dx} \right)^2}} \tag{29}$$

Where:

$$\frac{dZ}{dx} = \frac{\Delta Z}{L} f'(\xi) \tag{30}$$

For conventional and semi-buried inlets, the section lies in the normal plane of the centerline. Therefore, the major-axis direction of the ellipse can be taken as the global (Y)-axis direction, namely

$$\hat{\mathbf{e}}_1 = (0,1,0) \tag{31}$$

The minor-axis direction of the ellipse can then be determined by the cross product between the centerline tangent vector and the major-axis direction:

$$\hat{\mathbf{e}}_2 = \text{normalize}(\hat{\mathbf{t}} \times \hat{\mathbf{e}}_1) \tag{32}$$

For the embedded inlet, the actually generated section does not always coincide with the normal plane of the centerline. Therefore, the sectional normal vector must be corrected according to the sectional orientation factor. In this case, the major-axis direction of the ellipse is still defined as

$$\hat{\mathbf{e}}_1 = (0,1,0) \tag{33}$$

While the minor-axis direction is determined by the corrected sectional normal vector and the major-axis direction:

$$\hat{\mathbf{e}}_2 = \text{normalize}(\mathbf{n} \times \hat{\mathbf{e}}_1) \tag{34}$$

Since all sections are symmetric with respect to the XZ plane, the major-axis direction of the ellipse can be uniformly defined along the Y-axis. Accordingly, to make the formulation applicable to conventional, semi-buried, and embedded inlets, the sectional basis vectors can be written in a unified form as

$$\begin{aligned} \hat{\mathbf{e}}_1 &= (0,1,0) \\ \hat{\mathbf{e}}_2 &= \text{normalize}(\mathbf{n}_s \times \hat{\mathbf{e}}_1) \\ \mathbf{n}_s &= \text{normalize}\left[(1-\eta)\hat{\mathbf{t}} + \eta(0,0,1) \right] \end{aligned} \tag{35}$$

In this way, the sectional coordinate generation process for all three inlet configurations can be described within a unified local-coordinate framework.

3.5 Unified Formulation

In summary, the unified parameterization method for the three inlet configurations essentially determines the position of each spatial point in the axial, circumferential, and sectional radial directions. First, the centerline $\mathbf{C}(\xi)$ defines the axial location of the section center in three-dimensional space. Then, the sectional basis vectors $\hat{\mathbf{e}}_1$ and $\hat{\mathbf{e}}_2$ determine the major- and minor-axis directions within the sectional plane. Finally, the sectional parameters ((u,v)) define the two-dimensional geometry of the section and the corresponding major and minor semi-axis dimensions.

Therefore, for any given axial position and circumferential parameter , a spatial point on the inlet surface can be uniformly expressed as:

$$\mathbf{P}(\xi, s) = \mathbf{C}(\xi) + s(\xi, s)\left[u(\xi, s)\hat{\mathbf{e}}_1 + v(\xi, s)\hat{\mathbf{e}}_2 \right] \tag{36}$$

With this unified expression, conventional, semi-buried, and embedded inlet configurations can be described within the same parametric modeling framework.

The main variables and their prescribed values used in the unified parameterization process are summarized in the following table.

Table 1 - Definition and default values of key parameters for the unified inlet model

Parameter	Symbol / Description	Default Value
Outlet diameter	D	60mm
Length ratio	L/D	5.5
Baseline offset	$\Delta Z_1 / D$	1.3
Installation clearance	h/D	0.2
Centerline coefficients	A,B,C	3,-2,0
Area-distribution coefficients	D,E,F	3,-2,0
Inlet minor semi-axis	b/D	0.37
Section recovery	ξ_{rec} / D	2.6
Inlet inclination angle	θ	30°
Major-axis width contraction angle	β	0.5

4. Schematic of Different Inlet Configurations

4.1 Conventional inlet

When the values are set to (1,0,0) the centerline and cross-sectional area variation law of the conventional inlet are shown in the following figures:

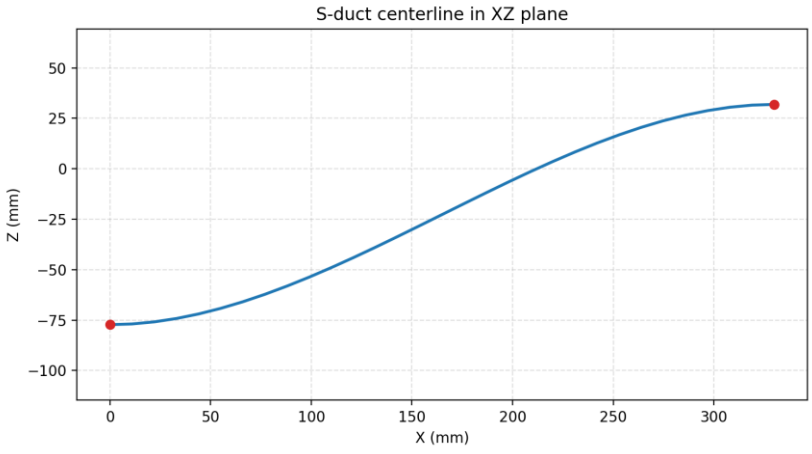


Figure 2 - Centerline profile of the conventional inlet

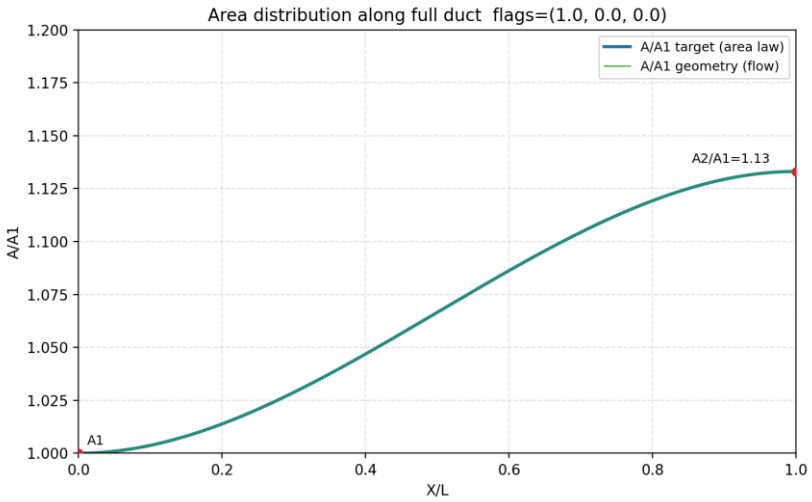


Figure 3 - Cross-sectional area distribution of the conventional inlet

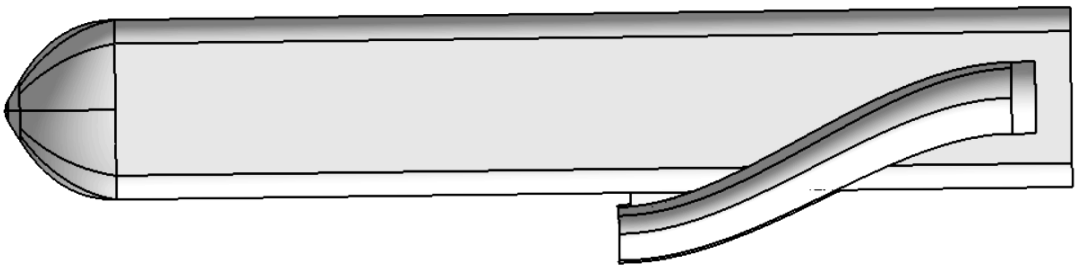


Figure 4 - Cross-sectional view of the conventional inlet

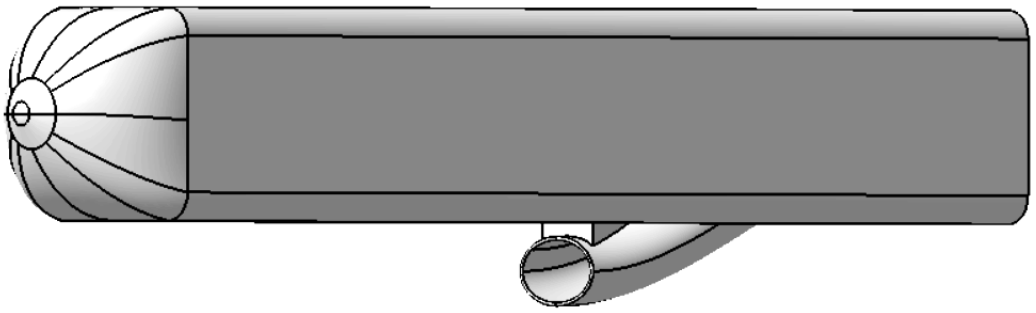


Figure 5 - model of the conventional inlet

4.2 Semi-buried inlet

When the values are set to (0,1,0) the centerline and cross-sectional area variation law of the semi-buried inlet are shown in the following figures:

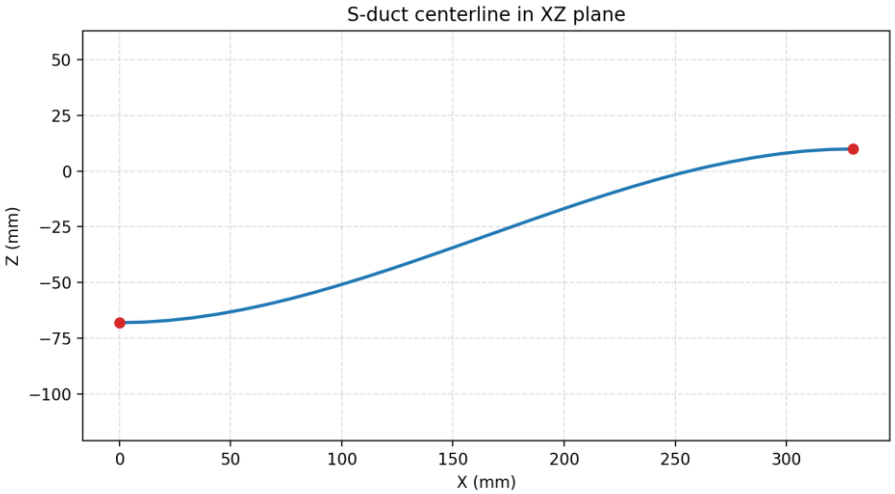


Figure 6 - Centerline profile of the semi-buried inlet

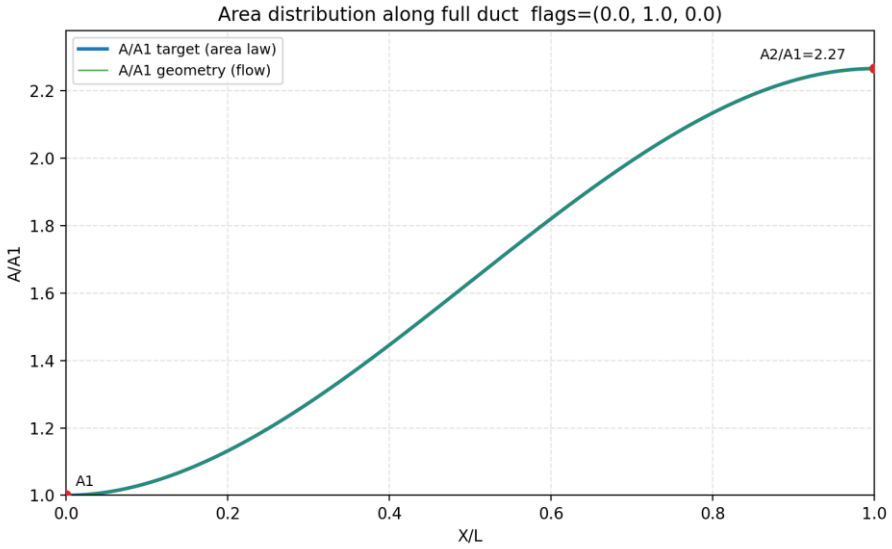


Figure 7 - Cross-sectional area distribution of the semi-buried inlet

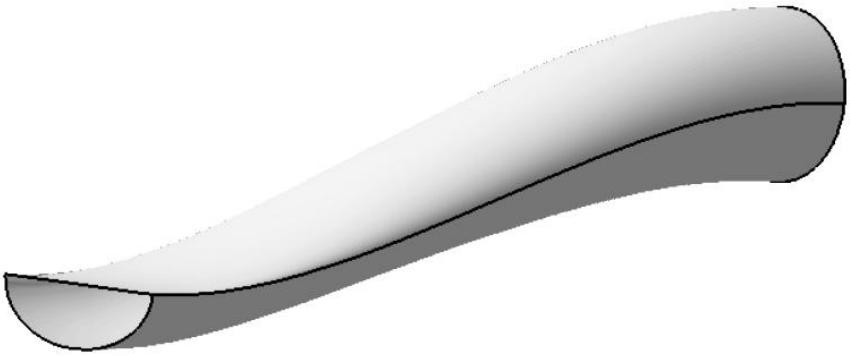


Figure 8 - model of the semi-buried inlet

4.3 Embedded inlet

When the values are set to (0,0,1) the centerline and cross-sectional area variation law of the embedded inlet are shown in the following figures:

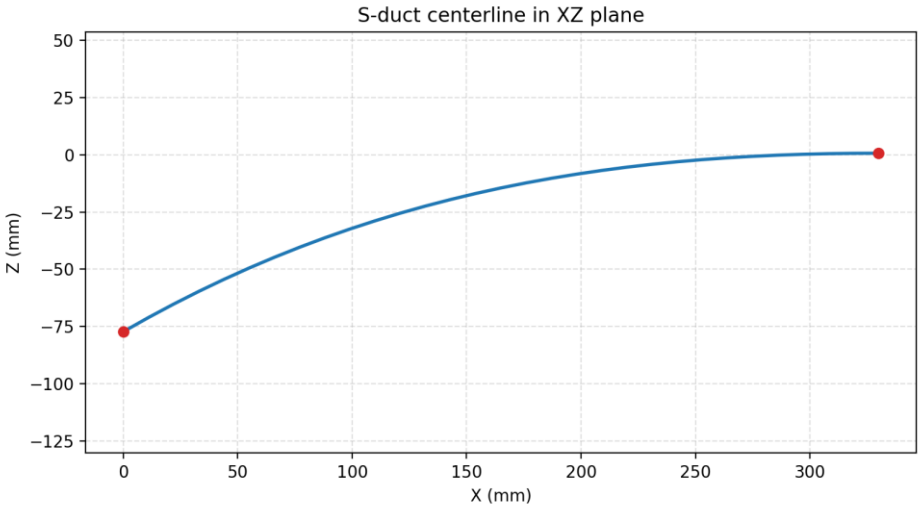


Figure 9 - Centerline profile of the embedded inlet

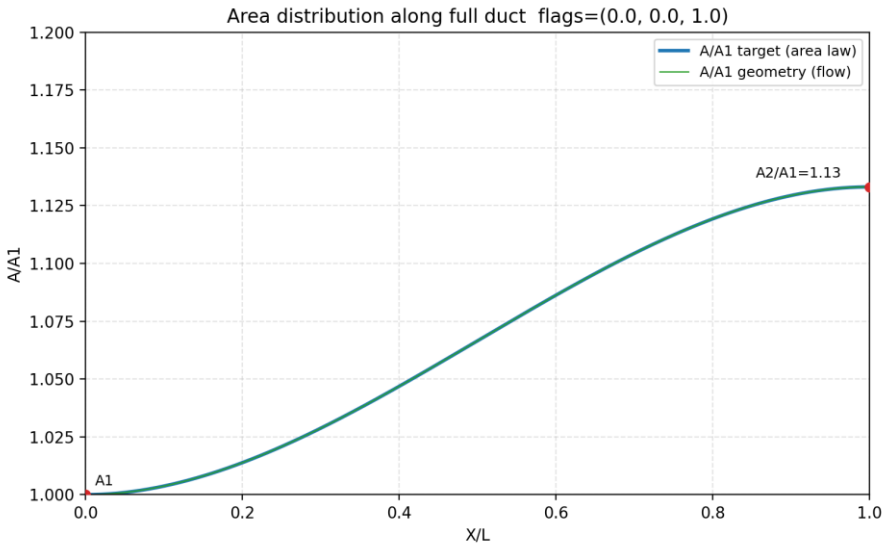


Figure 10 - Cross-sectional area distribution of the embedded inlet



Figure 11 - model of the embedded inlet

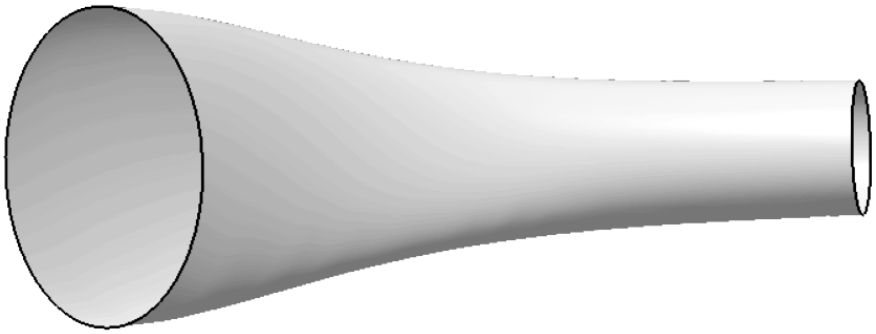


Figure 12 - Bottom view of the embedded inlet model

5. Conclusions

This study develops a unified parametric modeling method for conventional, semi-buried, and embedded inlets, aiming to address the difficulty of describing different inlet configurations within a consistent parameter system. By analyzing the common and distinct geometric characteristics of the three inlet types in terms of centerline definition, cross-sectional area distribution, inlet cross-sectional shape, sectional transition, and sectional orientation, configuration control variables are introduced to distinguish different inlet layouts within a unified framework. The proposed method enables parametric descriptions of the centerline design, area distribution, elliptical section variation, and three-dimensional sectional coordinate generation. For the conventional inlet, a complete elliptical inlet section is adopted to represent the exposed entrance geometry. For the semi-buried inlet, a partial elliptical section and a section-recovery function are used to describe the geometric coupling between the inlet and the vehicle surface. For the embedded inlet, the angular variation between the inlet section and the normal plane of the centerline is further considered, and a sectional orientation transition function is introduced to ensure a smooth transition from the actual generated section to the normal-plane section. Based on the developed method, geometric modeling validations are conducted for different inlet configurations. The results show that the proposed method can effectively generate conventional, semi-buried, and embedded inlet models while maintaining good geometric continuity and configuration adaptability. This unified parametric modeling method provides a foundation for rapid geometric generation, configuration comparison, and subsequent aerodynamic optimization of missile inlets.

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