Preliminary Investigation on the Impact of Missile Design on its Aerodynamic Features

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ABSTRACT

The dependence of aerodynamic features of a conventional missile on its configuration is examined. The features in concern are the zero-lift drag coefficient, the lift-curve slope and the center of pressure location. These coefficients are estimated using a commercial reliable tool that is used for conceptual design and preliminary sizing of rockets of simple shapes.

KEYWORDS: *Aerodynamic coefficients, Missile aerodynamics, Surrogate models.*

NOMENCLATURE

B	nose roundness	L	normalized conical nose section length
b	wing semispan [m]	L_N	total nose length [m]
$\boldsymbol{C_r}$	normalized wing root chord	R	missile radius [m]
$\boldsymbol{C_t}$	normalized wing tip chord	r	nose tip roundness radius [m]
$\boldsymbol{C_{Do}}$	zero-lift drag coefficient	S_F	wing planform area [m2]
$C_L{}^{\alpha}$	lift curve slope [rad-1]	$\boldsymbol{x_{cp}}$	normalized center of pressure location
D	missile caliber [m]	δ_c	conical nose semi-apex angle
l_c	length of conical nose section [m]		
l	overall missile length [m]		

1 INTRODUCTION

Predicting the aerodynamic characteristics of a missile is a crucial step in the procedure of missile system design. These values are fundamental inputs to the subsequent calculations of flight trajectory, accuracy, and lethality. In addition, the processes of developing new missiles or upgrading existing ones involve the estimation of aerodynamic coefficients.
For given flight conditions, the aerodynamic characteristics of a missile are solely dependent on its airframe configuration. Understanding this dependence is important for any missile airframe designer. This dependence is obvious and needs no proof. The objective of this paper however, is to quantize the dependence of main aerodynamic features on the missile airframe design. The aerodynamic features are estimated using a simplified engineering tool of an acceptable accuracy as far as preliminary design is concerned.

2 CASE STUDY

The missile examined in this study is the conventional fin-stabilized unguided ground-launched short-range tactical missile Luna-M [1]. The configuration of the missile is a spherically-blunted cone-cylinder of caliber $D = 544\ mm$ with four right-trapezoidal stabilizing fins at the end of the body. The figure below illustrates the missile configuration, dimensions are in mm.

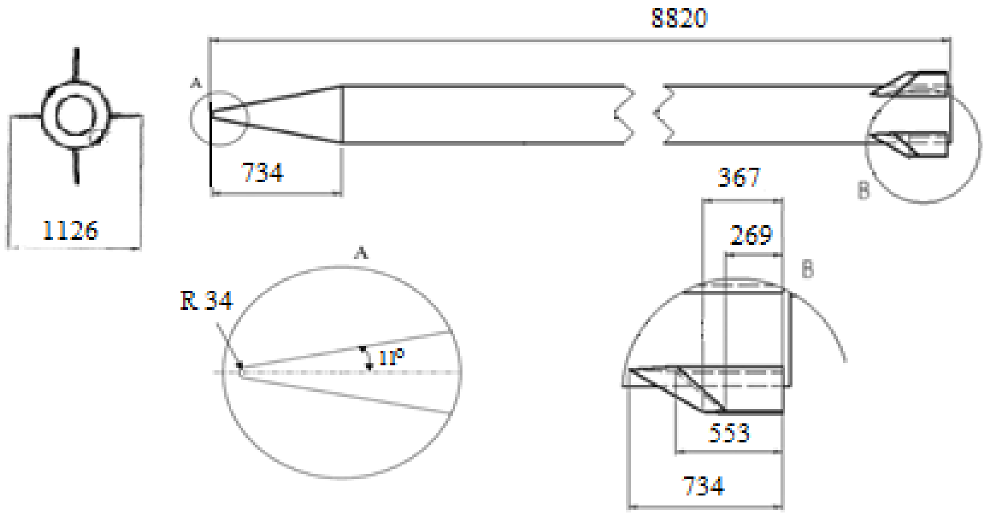


Figure 1: Configuration of the case study missile, dimensions are in mm

The operating conditions are selected corresponding to flight Mach number of 1.5 at sea level conditions in a standard atmosphere.

3 METHODOLOGY

3.1 Definition of the design parameters

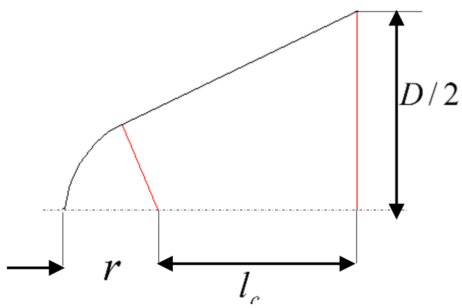
The objective is to explore the impact of varying the missile configuration on its aerodynamic coefficients. The missile overall length, l, caliber, D, and fin area, S_F are kept unchanged as the baseline configuration (Fig. 1) whereas other dimensions of other geometric elements of the missile are varied. In addition, the distance from missile base to fin trailing edge at root is assumed to be unchanged as the baseline configuration. For the un-winged body, the varying dimensions are:
- radius of nose hemispherical tip,
- nose cone semi-apex angle,
- nose length, and
- cylindrical body length.

For the fin, the dimensions are:
- root chord,
- tip chord,
- span,
- leading edge sweep angle, and
- distance from nose tip to fin leading edge at root.

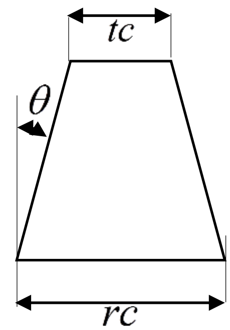
Among the nine geometric dimensions above, only five are adopted to be the independent parameters and are allowed to vary within reasonable arbitrarily-defined ranges. The remaining four geometric elements can be calculated based on geometric constraints. For a more generic representation, the independent parameters representing linear dimensions are normalized with respect to the missile caliber. The normalized independent parameters and the corresponding ranges of variation are listed in the table below.

Table 1. Missile independent geometric parameters and their corresponding ranges of variation

Geometric parameter	Range of variation	
	Lower limit	Upper limit
Nose tip roundness, $B = r/(0.5D)$, Fig. 2.a	0	1
Length of conical part of the nose, $L = l_c/D$, Fig. 2.a	0	5
Fin tip chord, $c_t = tc/D$, Fig. 2.b	0	4
Fin root chord, $c_r = rc/D$, Fig. 2.b	0.2	4
Fin leading edge sweep angle, θ, Fig. 2.b	-70^o (forward sweep)	$+70^o$ (backward sweep)



(a) spherically-blunted nose



(b) trapezoidal fin

Figure 2: Geometric parameters of the missile

The remaining dependent geometric elements are calculated based on geometric constraints using the following relations:

1- nose cone semi-apex angle:

$$\delta_c = cos^{-1}\left[\frac{Rr + l_c\sqrt{{l_c}^2 - r^2 + R^2}}{{l_c}^2 + R^2}\right]$$

2- nose length:

$$L_N = l_c + r$$

3- cylindrical body length:

$$L_c = l - L_N$$

4- fin span:

$$b = 2S_F/(tc + rc)$$

5- distance from nose tip to fin leading edge at root:

$$x_F = l - rc$$

3.2 Sample selection

By independently varying the geometric parameters listed in Table 1, distinct missile configurations are attained. The proper combinations of these parameters is important in selecting the designs in this 5D design space. The selected designs (locations in the design space) should be uniformly distributed as well

as space-filling. Various sampling techniques are available however, the Latin Hypercube Sampling [2] is adopted in this study. Using DoE toolbox in Matlab [3], 500 samples are generated.
For each of the 500 designs, the aerodynamic coefficient in concern namely, zero-lift drag coefficient, C_{Do}, lift curve slope, ${C_L}^{\alpha}$, and location of center of pressure, x_{cp}, are estimated. The flight conditions are selected to be corresponding to sea-level standard atmospheric conditions with a speed of Mach 1.5 (which is the nominal Mach value experienced by the missile during powered trajectory [1]).

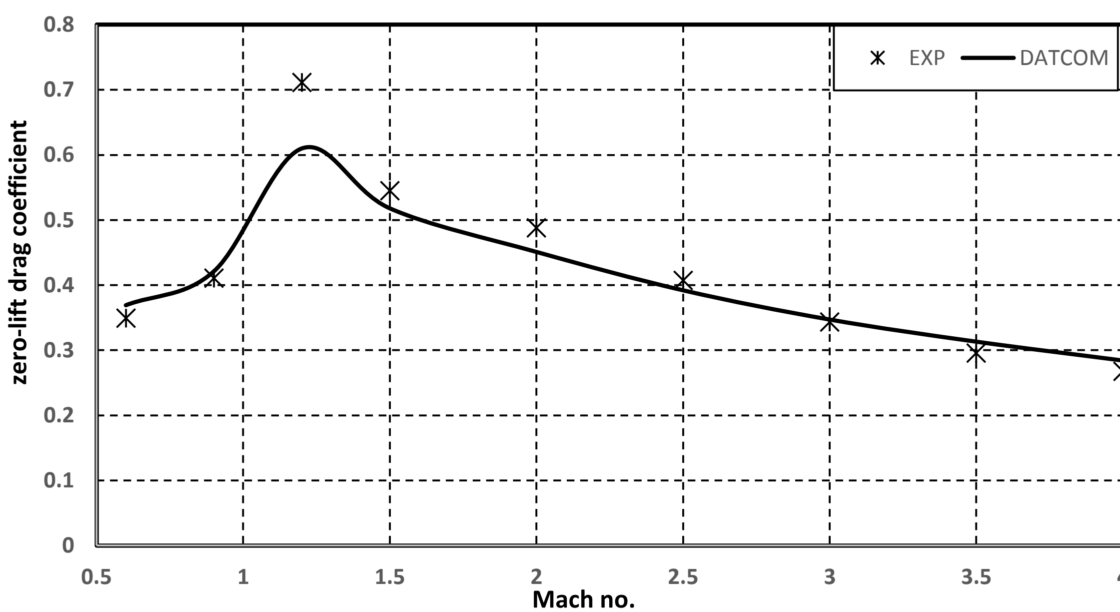
3.3 Aerodynamic prediction tool

Missile Datcom [4] is a reliable preliminary aerodynamic design toll that has been used in a huge body of studies over the decades and until recently (e.g. [5, 6]). In this work, the commercial version of the toll with GUI that is available on the web [7] is implemented.

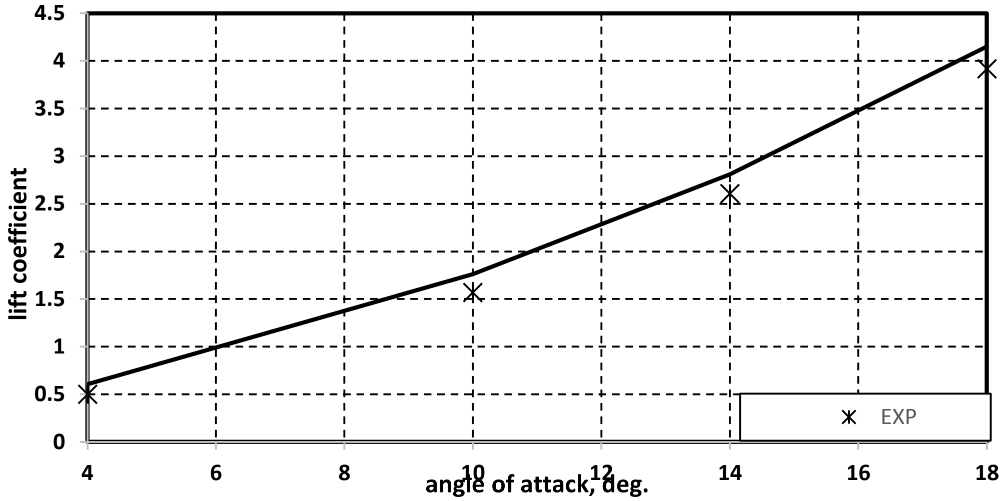
4 RESULTS AND DISCUSSION

4.1 Validation of aerodynamic calculation tool

The studies focusing on the aerodynamic characteristics of the baseline design of the missile in concern have been studied by many researchers, e.g., [8-10]. In this study, the experimentally measured values of the missile available in [8] are utilized to assess the validity of the used aerodynamic prediction tool. Figure 3 below compares the zero-lift drag coefficient (at different Mach values) and the lift coefficient (at Mach 1.5) of the baseline missile as predicted by Missile Datcom and measure experimentally [8]. The comparison shows the satisfactory accuracy of the used tool especially in the supersonic regime of freestream Mach number even at high incidence angles.



(a) Zero-lift drag coefficient vs. Mach number

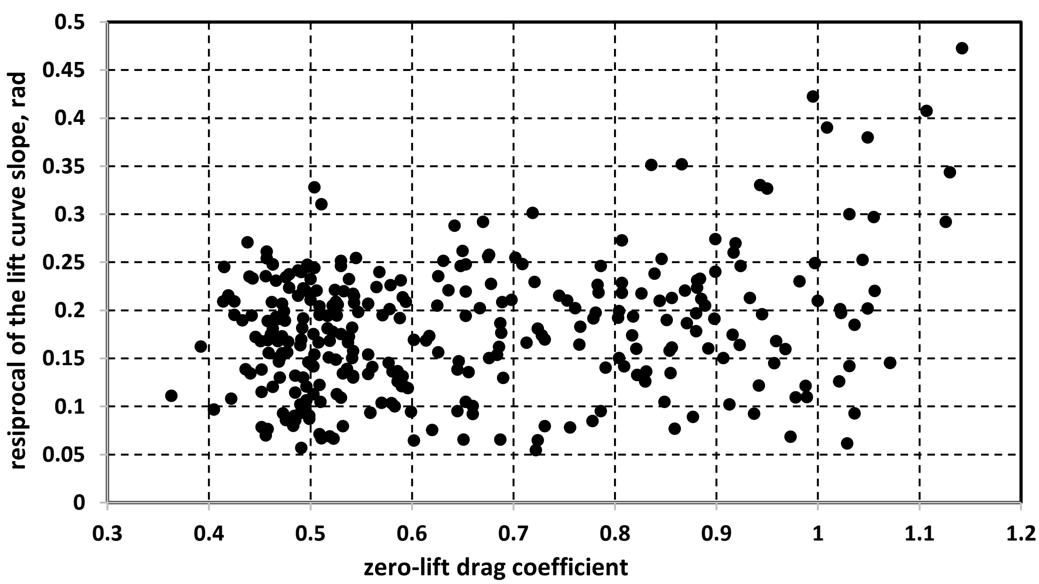


(b) Lift coefficient vs. incidence angle at Mach 1.5 freestream

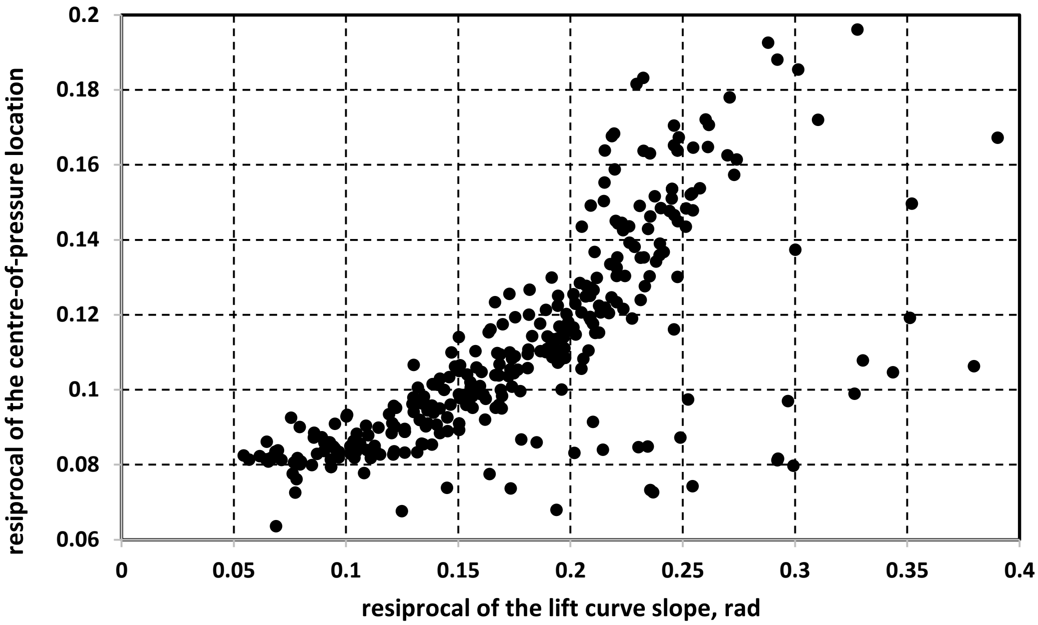
Figure 3: Validation results for the aerodynamic prediction tool

4.2 Realization of the objective space

The figures below show the loci of all 500 sample designs in the objectives space. Since three objectives are in concern, each pair of objectives is displayed separately. Figure 4a shows preliminary realization of the objective space with zero-lift drag coefficient and reciprocal of lift slope as the coordinates. A state of competition is clear between the two objectives. This implies that a single design that satisfies both minimum drag and maximum lift is unattainable and a tradeoff between the two design objectives is necessary. In Fig. 4b, the lift curve slope and the center of pressure location objectives are illustrated. The figure shows that these two objectives are less competing and a single design may satisfy both objectives.



(a)



(b)

Figure 4: Preliminary objective space of the case study

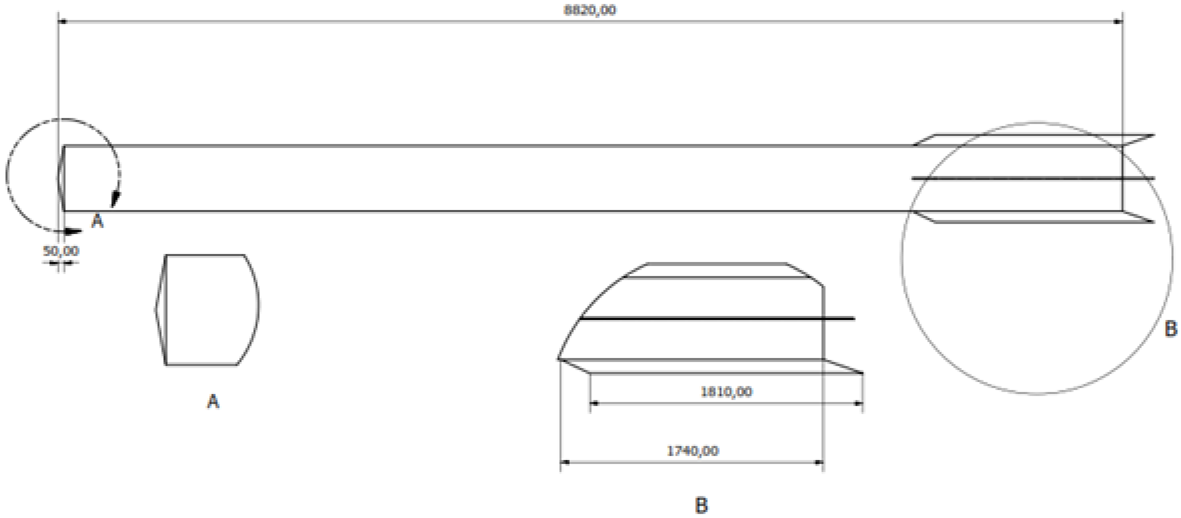
4.3 Designs of extreme aerodynamic performance

The table below lists the features of the designs with extreme aerodynamic performance among the set of samples involved in the study. Clearly, the design that yields the maximum drag coefficient is highly blunt. The length nose cone is only 0.5% of the overall missile length with a sharp pointed tip corresponding to nose slenderness ratio of 0.09. It is in fact the sample with the shortest nose cone. In contrast, the design that generates the minimum drag has a nearly pointed nose cone which length is 29% of the overall missile length; a nose slenderness ratio of 4.7.

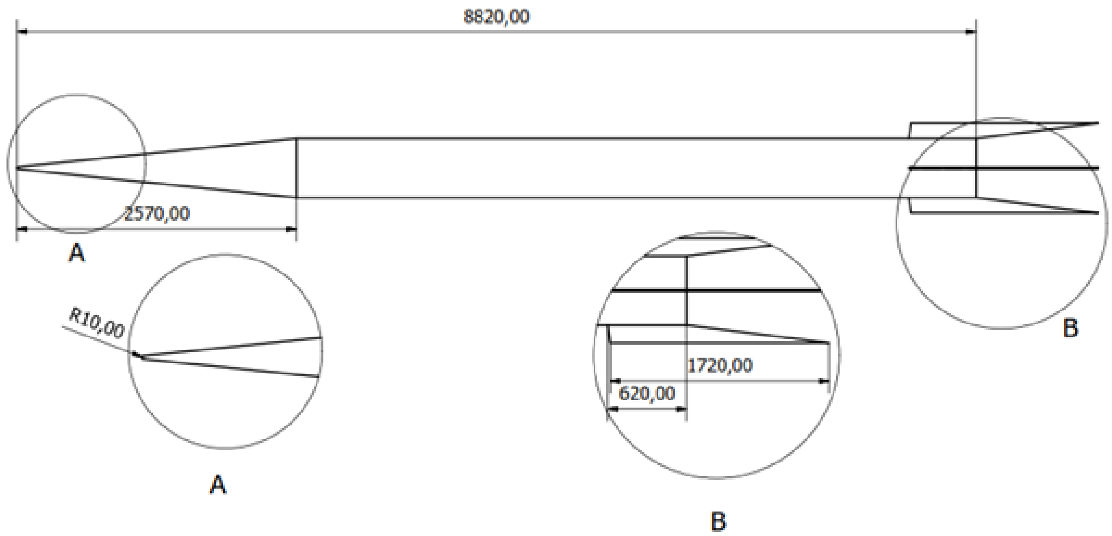
Table 2. Features of designs of extreme aerodynamic performance

Geometric parameter	**Units**	**Aerodynamic performance criteria**					
		C_{Do}		${C_L}^{\alpha}$		x_{cp}	
		Max. =1.888	Min. =0.363	Max. =13.386	Min. =0.8457	Max. =23.467	Min. =2.696
Nose tip roundness	[cm]	0	1	6	15	15	26
	normalized	***0.0***	***0.04***	***0.22***	***0.55***	***0.55***	***0.96***
Length of conical part of the nose	[cm]	5	257	64	268	268	31
	normalized	***0.09***	***4.72***	***1.18***	***4.93***	***4.93***	***0.57***
Fin root chord	[cm]	174	62	192	15	15	34
	normalized	***3.20***	***1.14***	***3.53***	***0.28***	***0.28***	***0.63***
Fin tip chord	[cm]	181	172	165	86	86	204
	normalized	***3.33***	***3.16***	***3.03***	***1.58***	***1.58***	***3.75***
Fin leading edge sweep angle		$+65^o$	$+9^o$	$+1^o$	$+66^o$	$+66^o$	$+3^o$

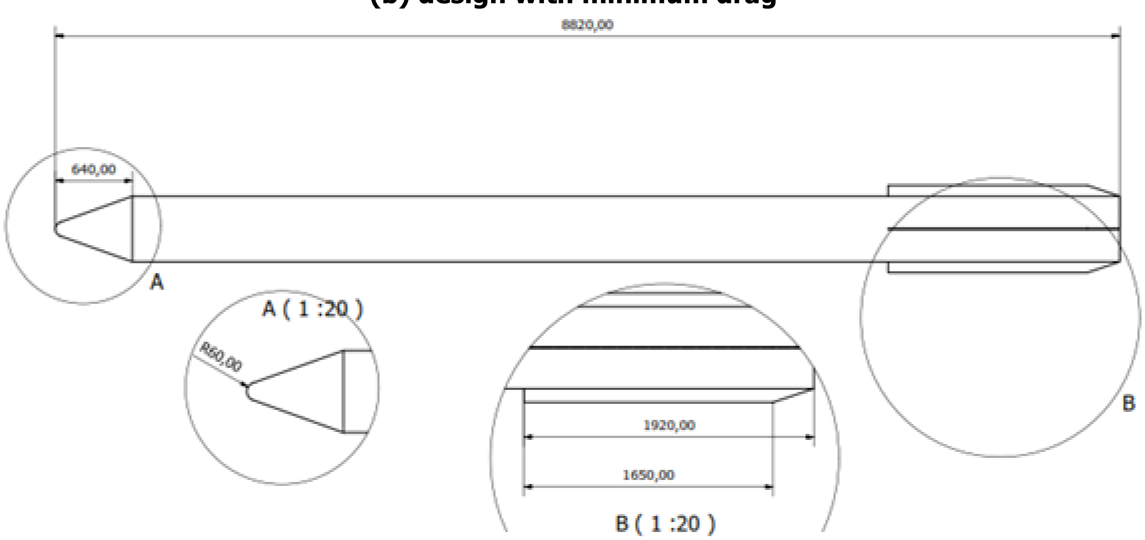
The set of figures below illustrate the airframe configurations of designs with extreme aerodynamic characteristics.



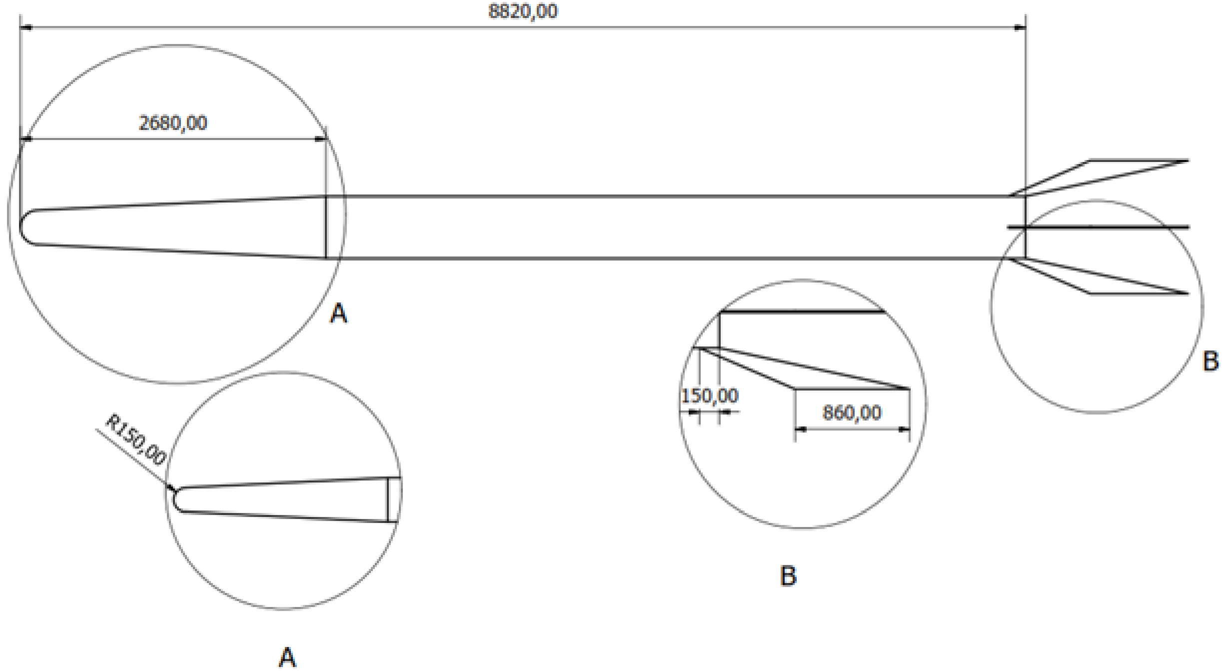
(a) design with maximum drag



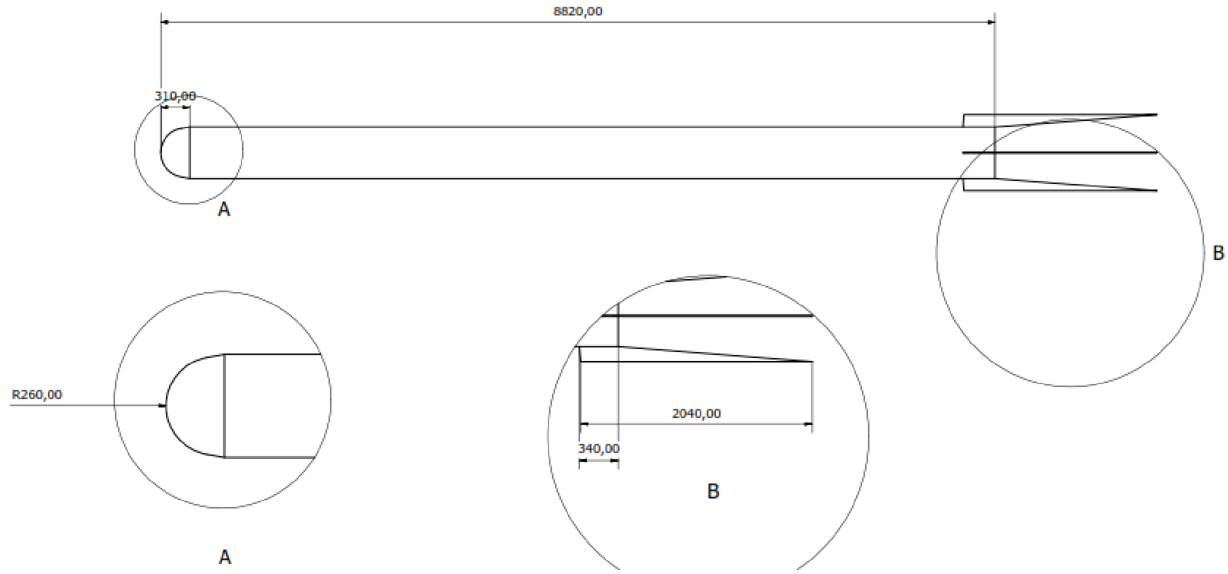
(b) design with minimum drag



(c) design with maximum lift



(d) design with minimum lift (and maximum stability)



(e) design with minimum stability

Figure 5: Illustration of designs with extreme aerodynamic characteristics

Clearly, the design that produces the maximum drag is extremely blunt. It has the shortest nose length with no nose roundness. In contrast, the design with a very long nose and a slight tip roundness produces the minimum drag. This indicates that the missile drag is mainly driven by the forebody configuration. The design that yields the maximum lift curve slope is characterized by very long chord and, hence, a very narrow span. Such design would maximize the wing-body interference and hence, increase the lift capability of the wing. In addition, the nose that has a relatively high semiapex angle adds to the overall missile lift. The design that provides minimum lift curve slope has an unrealistic wing design that experiences almost no interference with the body. The nose is also very long such its contribution to lift is minimized. This design is the one that provides the highest stability criteria (expressed as the distance to the missile pressure center location).

4.4 Surrogate representation of the missile aerodynamic features

It is interesting to attempt visualizing the relations between the missile aerodynamic features and its design parameters based on data extracted from the prediction tool. This simplest way to do this is to construct metamodels (surrogates) for each of the missile aerodynamic features. In this study, the first-order regression polynomial response surface metamodel is implemented. The tool developed by Viana [11] is utilized. Based on the data obtained for the 500 sample designs, the zero-lift drag coefficient is expressed in terms of the normalized geometric parameters as:

$$C_{D0} = 0.7728 - 0.0056\,(C_r) - 0.0087(C_t) - 0.00055\,(\theta) + 0.5531(B) - 0.0891\,(L)$$

By comparing the coefficients of all terms of the above expression, it can be inferred that nose tip roundness and length are the most dominant parameters. These two parameters have the highest coefficients. In contrast, the geometric parameters of the missile wing are the least dominant. As indicated by the signs, the drag increases as the nose length decreases and nose roundness increases. However, it should be noted that both nose length and tip roundness contribute to the nose bluntness; the key design feature that dictates the drag. Similarly, the lift curve slope of the missile can be expressed as:

$$\boldsymbol{C_L}^{\boldsymbol{\alpha}} = 7.2587 - 0.2133(C_r) - 0.2945(C_t) - 0.0093(\theta) - 0.1062(B) + 0.1936(L)$$

From the above expression, it can be inferred that wing geometric parameters dominate the lift curve slope value. Other parameters are of a less importance. As inferred by the signs, the lift curve slope varies directly with nose length and inversely with other parameters. Finally, the location of center of pressure can be expressed in terms of the design parameters according to the following expression:

$$\boldsymbol{x_{cp}} = 10.779 - 0.453(C_r) - 0.063(C_t) + 0.0023(\theta) - 0.3105(B) - 0.0444(L)$$

Similar to lift curve slope, the nose roundness and wing root chords are the dominant design parameters as far as center of pressure location is concerned.

5 CONCLUSIONS

The objective of the present study was to understand the impact of the missile design on its aerodynamic characteristics. Five design parameters fully describing the design a simple fin-stabilized tactical missile were investigated. These design parameters were varied and the impact of their variation of the aerodynamic characteristics of the missile was explored. Focus was made on zero-lift drag, lift slope, and location of missile center of pressure. 500 different designs were developed and their aerodynamic characteristics were estimated using a reliable empirical prediction tool. The three-dimensional space of the sample designs was realized and the designs with extreme behavior were illustrated. Simplified expressions were developed using polynomial regression surrogate. The study was intended to shed more light on the impact of missile airframe design on its aerodynamic characteristics. The study can be extended by optimizing the missile airframe design taking into consideration the compromise among different aerodynamic characteristics. Other design considerations that aerodynamics such as fuselage inner volume should also be taken into account.

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