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Outer Geometry Optimization of an Air-to-Air Missile

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Abstract:

The aim of the paper herein is to develop efficient optimization-based aerodynamic design for short term air-to-air missile outer geometry. Dimensioning of a product can be performed by trial-and-error process conducted by an experienced designer or by the tests until the requirements are verified. When the computer aided design have been introduced in the design and manufacturing processes, the time spent on making designs are significantly reduced. Optimization methods are also involved in the design processes. They have been developed in order to choose best element from initial set of elements with given objective which has minimizing or maximizing function such as maximizing the product efficiency and minimizing the costs. They basically divide into two categories as gradient and genetic algorithms differing from each other to find the best suitable combination. In aviation industry, many studies have been carried out with implementation of surrogate models on analysis and using design of experiments methods within different optimization algorithms. In this study, body and aerofoil dimensions are determined as outer geometry parameters. These parameters are used as the inputs for flight simulation software in order to calculate aerodynamic parameters. Finally, aerodynamic parameters are used for the guidance simulation of the missile. Surrogate models which are statistical methods and simulate the analyses in order to reduce the calculation times are also used in the optimization process. All codes and simulation programs are integrated in ModeFrontier™ software. ModeFrontier™ is also used for performing different optimization methods such as gradient and genetic based algorithms.

Key words: Optimization, missile geometry, surrogate models, flight simulation, guidance

1. Introduction

Air-to-air missile guidance is a nonlinear control problem defined over a time interval whose objective is to generate trajectory commands for the missile according to some specific law such that the distance between the missile and target will decrease to zero. Figure 1 is a functional block diagram of a missile guidance system. [1]

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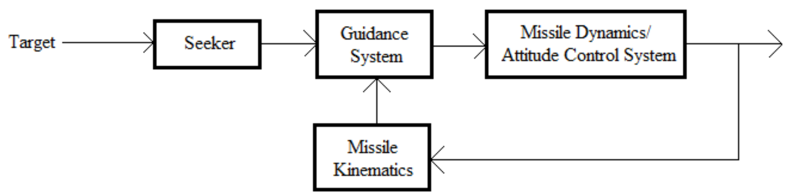

Figure 1. Functional Block Diagram of a Missile Guidance System

In Figure 1, target information is obtained by seeker of the missile and sent to guidance system. Attitude control system works with guidance system to calculate necessary trajectory commands using that information.

There is a wide range of control laws available. These guidance schemes range from classical techniques which assume constant target velocity to more advanced control laws which assume at least statistical knowledge of target acceleration. [2] Guidance laws typically fit within the following five categories for short-range tactical missiles, the first three of which are the well-known classical techniques: line-of-sight (LOS), pursuit, proportional navigation guidance (PNG), optimal linear, and other guidance laws dominated by differential game methods. [3] In our study, we will be dealing with Proportional Navigation as a Guidance System of the missile. Therefore, details of the proportional navigation will be taken into account. Proportional navigation (PN) is a well-known guidance law that performs very efficient in a large variety of cases. The general idea of PNG is to turn the heading of the object toward some desired direction as rapidly as possible by commanding the object's accelerations which are proportional to the angular rate of such direction. A PNG homing system measures the rate of rotation of light of sight (LOS) from the object to the target. The guidance input is assigned proportional to the LOS rate, and requires the object to turn in the corrective direction, i.e., in the direction to reduce the LOS rate between the missile and target to zero. [4] In the most sense, optimization is the process of achieving the best outcome of a given operation while satisfying a set of given constraints. The cost (or objective) function is the term applied to this outcome that needs to be improved (or optimized). In a computational sense, this cost function is expressed as a scalar value and it is mathematically dependent on a set of design variables. The best solution of an optimization problem would be the set of design variables such that the cost function reaches its global minimum value. [5]

2. Materials and Method

The aim of the study herein is to develop efficient optimization-based aerodynamic design for short range air-to-air missile outer geometry for the purpose of minimization of its time of flight. Short range air-to-air missiles usually have infrared seeker as a guidance system to catch the target. They are also using thrust vectoring with the tail fin control at rocket motors to make sharp turns during the flight which make the missile more agile. The approach described herein to design control fins outer geometry of the missile with multidisciplinary optimization method.

Sample of short range air-to-air missile outer geometry is shown in Figure 2.

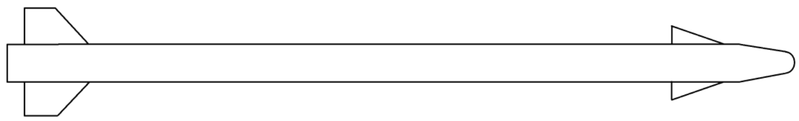

Figure 2. Short range air-to-air missile outer geometry

In a typical short range air-to-air missile, direction change is provided by fin movement which is placed at the aft of the missile body whereas the aerodynamic stability is controlled by the canards which are placed at the forward of the missile body. Missile and target are assumed to move in two-dimensions. Altitude of the missile during the interception phase is taken as 12.000 meters. Therefore, calculations will be made based on the lateral dynamics of the missile. The important parameters of the missile-target intercept are shown in Figure 3. R is the planar distance between missile and target. The elevation angles of the missile, target and R from the horizontal plane are θ_M, θ_R and θ_T respectively. Velocities of the missile and target are V_M and V_T respectively. Initial values of θ_R and R are assumed to be 45 degrees and 2000 m respectively while the missile is launching from the platform. V_T is assumed constant during the interception as 200 m/s whereas the θ_T is assumed zero during flight. To sum up, the target is moving on a horizontal plane with constant speed.

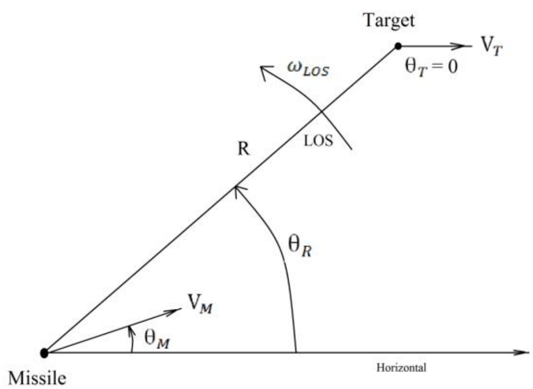

Figure 3. Missile-target intercept geometry

2.1. Theory/calculation

Unlike traditional separate subsystem analysis, integrated design process is chosen for missile components working with each other to drive the missile to hit the target. This is also called multidisciplinary design process. Workload and time will be reduced comparing to separate subsystem analysis. Exchange of information (input-output relation) between softwares is performed using this method.

Aerodynamic terms to be used on linearized and combined lateral equations in order to yield the lateral equations of motion for the missile are obtained. Missile Datcom™ software is used for aerodynamic computations. Missile body is assumed as axisymmetric. Outer casing of the missile is made of aluminum structural parts. Therefore, Roughness Height Rating (RHR) is selected from the Missile Datcom User's Manual which has a value of 125. Boundary layer type is modeled as fully turbulent. Since the base drag computed for the body geometry is included in the final computed axial force calculations, nozzle diameter for base drag calculation is taken into account. Separate two fin sets are specified on the missile as shown in Figure 2. Number of panels in both fin sets are chosen as four. From vertical center looking forward to the missile, first fin placed at the top of the missile and the other fins are evenly spaced around the missile body having roll angle of 90 degrees. Lateral stability derivatives calculated by Missile Datcom™ and their definitions are given in Table 1.

Table 1. Lateral stability derivatives and their definitions

Symbol	Representation in Missile Datcom™	Definition
C_{y_r}	CYR	Side-force Coefficient change with respect to Yaw Rate
C_{y_β}	CYB	Side-force Coefficient change with respect to Sideslip Angle
C_{n_r}	CLNR	Yawing Moment Coefficient change with respect to Yaw Rate
C_{n_β}	CLNB	Yawing Moment Coefficient change with respect to Sideslip
C_{n_p}	CLNP	Yawing Moment Coefficient change with respect to Roll Rate
C_{l_p}	CLLP	Rolling Moment Coefficient change with respect to Roll Rate
C_{l_r}	CLLR	Rolling Moment Coefficient change with respect to Yaw Rate
C_{l_β}	CLLB	Rolling Moment Coefficient change with respect to Sideslip Angle

Three lateral equations in the literature are obtained using the aerodynamic terms. From these equations, the lateral modes are determined and the various transfer functions for fin input derived and analyzed. Uncoupled and linearized lateral equations of motion are given in Eq.(2.1), Eq.(2.2) and Eq.(2.3) [6-7]. These equations are nondimensional.

$$-\frac{b}{2U}C_{y_p}\dot{\emptyset} - C_{y_\emptyset}\emptyset + \left(\frac{mU}{Sq} - \frac{b}{2U}C_{y_r}\right)\dot{\Psi} - C_{y_\Psi}\Psi + \frac{mU}{Sq}\dot{\beta} - C_{y_\beta}\beta = C_{y_a} \quad (2.1)$$

$$\frac{I_x}{Sqb}\ddot{\emptyset} - \frac{b}{2U}C_{l_p}\dot{\emptyset} - \frac{J_{xz}}{Sqb}\ddot{\Psi} + \frac{b}{2U}C_{l_r}\dot{\Psi} - C_{l_\beta}\beta = C_{l_a} \quad (2.2)$$

$$-\frac{J_{xz}}{Sqb}\ddot{\emptyset} - \frac{b}{2U}C_{n_p}\dot{\emptyset} - \frac{I_z}{Sqb}\ddot{\Psi} - \frac{b}{2U}C_{n_r}\dot{\Psi} - C_{n_\beta}\beta = C_{n_a} \quad (2.3)$$

Parameters stated in Eq. (2.1) , Eq. (2.2) and Eq. (2.3) and their definitions are given in Table 2.

Table 2. Parameter definitions in lateral equations

Parameters	Unit	Definitions
b	m	Wingspan
U	m/s	Velocity of missile
S	m^2	Reference area of missile
m	kg	Mass
q	$\frac{N}{m^2}$	Dynamic pressure
I_x	$kg.m^2$	Moment of inertia about x-axis
I_z	$kg.m^2$	Moment of inertia about z-axis
J_{xz}	$kg.m^2$	Products of inertia
C_{y_p}	-	Side-force Coefficient change with respect to Roll Rate
$C_{y_\emptyset}$	-	$\frac{mg}{Sq}\cos(\beta)$
C_{y_Ψ}	-	$\frac{mg}{Sq}\sin(\beta)$

Since the term C_{y_p} results from the side force on the vertical tail caused by a rolling velocity, C_{y_p} can be neglected. This rolling velocity causes lift to be produced by the vertical tail causing a force in the y direction; however, this force is small, since the rolling velocity must be small in order to decouple the equations. In general, J_{xz} has small values compared to principle moments of inertia which are, in this case, I_x and I_z. Therefore, J_{xz} is neglected [8]. $\emptyset$ is the roll angle of the missile with respect to horizantal line shown in Figure 4.

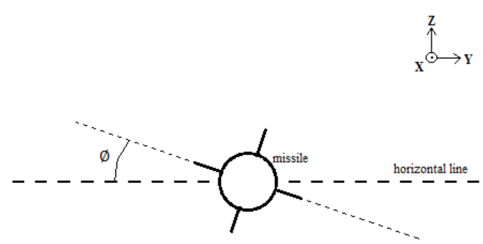

Figure 4. Roll angle of the missile body

β is the sideslip angle. Ψ (yaw angle) is the angle between longitudinal axis and the flight path of the missile. β and Ψ are shown in Figure 5.

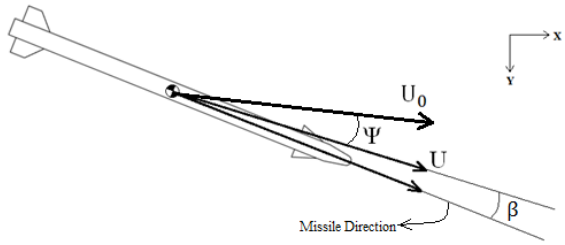

Figure 5. Yaw and sideslip angle of the missile body

Firstly, homogeneous equation is obtained in order to have the solution of lateral equations. With initial conditions equal to zero and substitution of the values of roll moment and yaw moment with respect to fin deflection (δ_a) yields the transfer function for δ_a as input and Ψ as output. As a result, it is determined that the change of missile direction due to the fin deflection for specified conditions. Figure 6 represents a block diagram of an air-to-air missile autopilot. As the missile is symmetrical with respect to the Y and Z axes, the longitudinal and lateral autopilots are the same. Since we are dealing with the motion on the lateral plane, only the lateral autopilot is taken into account.

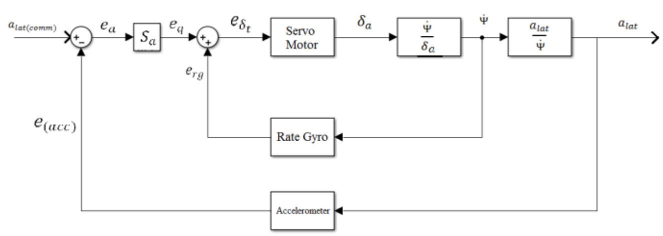

Figure 6. The block diagram of missile autopilot

For proportional navigation guidance the missile is commanded to turn at a rate proportional to the angular velocity of the line of sight (LOS). The line of sight is defined as imaginary line from the missile to the target. The seeker, by tracking the the target, establishes the direction of the LOS, and the output of the seeker is the angular velocity of the LOS with respect to inertial space as measured by rate gyros mounted on the seeker. The magnitude of the angular velocity of the LOS which generates the angular velocity of the seeker is determined by the components of the missile and target velocity perpendicular to the LOS. The block diagram for the analysis of proportional navigation guidance is given in Figure 7 [9].

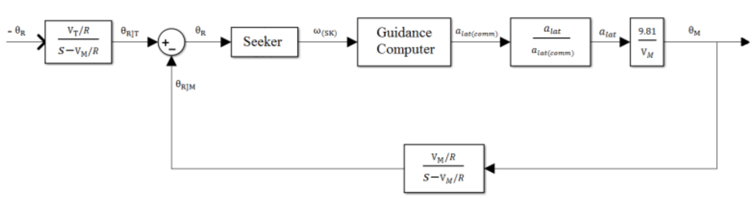

Figure 7. Block diagram for proportional navigation guidance

Since we are working on the simulation, these components are modelled by PID (proportional-integral-derivative) controller PID controller is used to control the missile. PID gains of the missile are tuned using the Matlab™ software.
In this study, realtime missile guidance is simulated on trajectory analysis. Velocity of the missile, center of gravity, mass and the moment of inertias on x and y axes are changing during the flight. Therefore, calculated aerodynamic parameters depending on the variables for an instant time used in transfer function are not valid every time. All time-varying parameters are revised by 0.1 second to simulate real scenario.
All branches are integrated in order to reduce workload and time. Exchange of information (input-output relation) between branches is performed by ModeFrontier™. Time-varying simulations, in a similar manner, are also performed on ModeFrontier™ using Subprocess node of the software. Each geometry generated by the optimization algorithm is subjected to simulation of individual missile flight. Time-varying parameters are revised every 0.1 second to have simultaneous transfer function reference input as θ_R and calculate the response of the system as θ_M. Aerodynamic parameters are changed during this interval and the affected transfer function obtained. ModeFrontier™'s Subprocess node is used for the simulations. Outer geometry generations are made on the Outer Loop of the node. Revision of the parameters in flight for each geometry is made on the Inner Loop of the node. In other words, the baseline design and the various subsystems are modified and the cycle is repeated until a design that meets the required performance parameters is obtained. These series of iterative steps is repeated for each subsystem. When the distance between missile and target becomes lower than 10 meters, iterations are stopped. Inner Loop and Outer Loop of the simulation are presented in Figure 8 and Figure 9 respectively.

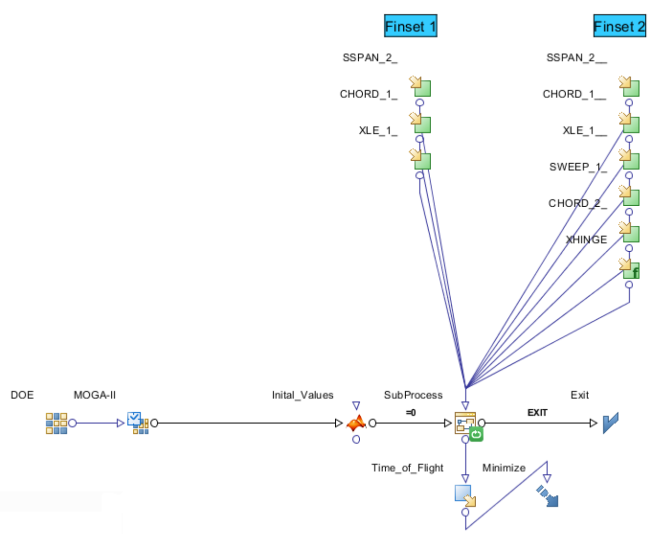

Figure 8. Outer loop of the simulation

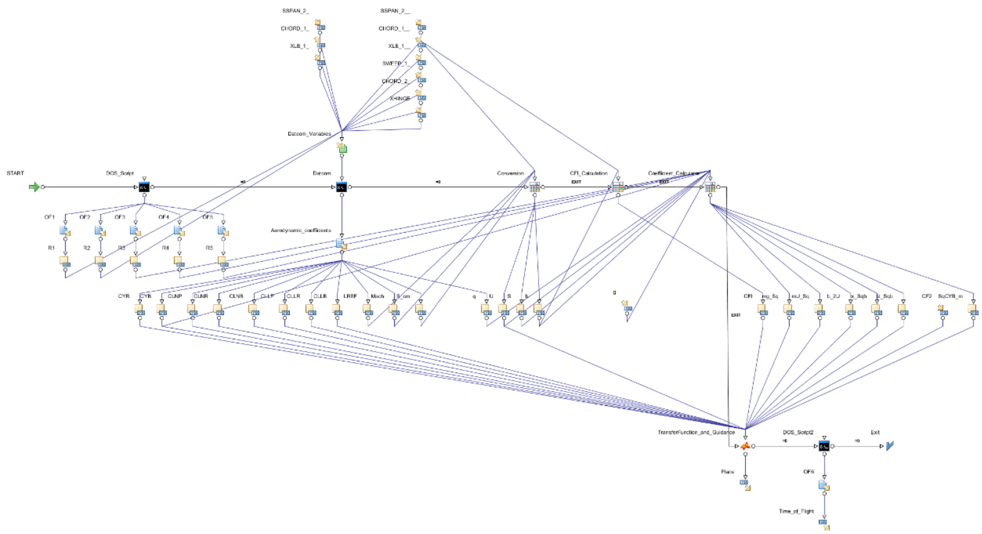

Figure 9. Inner loop of the simulation

Optimization problem was formulated for a tailfin guided missile, and shape optimization was performed to minimize the missile's flight time. The objective function was time of flight minimization, and the design variables were eight external shape variables which are shaping the canards and tailfins such that the root chord, tip chord, span, sweep and distance from the nose for the four canards and four tailfins. These variables are shown in Figure 10, Figure 11 and Figure 12.

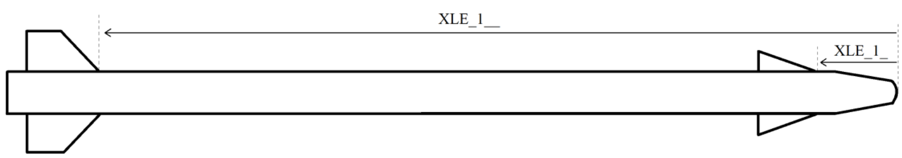

Figure 10. Variable of distance from the missile nose

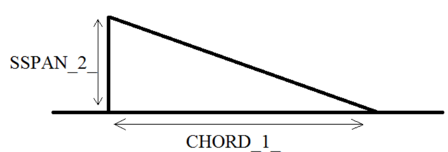

Figure 11. Variables of canard

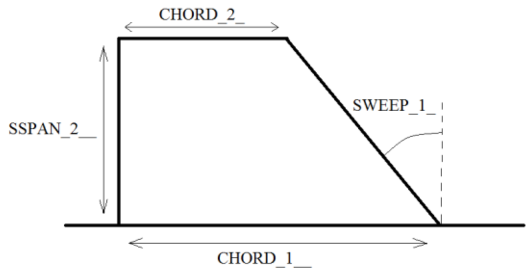

Figure 12. Variables of tailfin

Among the various existing optimization methods, Multi Objective Genetic Algorithm (MOGA-II) was selected. Total of 1080 designs are simulated on optimization process.

3. Results

As result of the 1080 simulations, optimum fin parameters are shown in Table 3.

Table 3. Optimized fin parameters

Fin Parameters	Optimized values
CHORD_1	37.7 cm
CHORD_1__	47.3 cm
CHORD_2_	30.1 cm
SSPAN_2_	9.1 cm
SSPAN_2__	27.3 cm
SWEEP_1_	41.9 degrees
XHINGE	293.3 cm
XLE_1_	47.8 cm
XLE_1__	265.3 cm

4. Discussion

Improvement of the study is also discussed in this section. Revision time of the time-varying parameters could have reduced to have results of flight time parameter in more number of digits. This can also provide a global optimum point among all designs. Other design variables such as diameter of missile, rocket motor thrust profile, and so forth, can be taken into account as well as canard and fin shape variables. Any variables regarding missile characteristic can be included in design process. Whole study can be carried out in three-dimensions as well.

5. Conclusions

In this study, efficient optimization-based aerodynamic design for short term air-to-air missile outer geometry in two dimensions is obtained. Aerodynamic terms are used on linearized and combined lateral equations in order to yield the lateral equations of motion for the missile. Laplace tranformation is applied to those equations to obtain transfer functions. Missile autopilot is modified as replacing the real components by PID controller in the simulations. Proportional navigation is chosed as guidance law because of its simplicity. Since velocity of the missile, center of gravity, mass and the moment of inertias about x and y axes are changing during the flight, these parameters are revised by 0.1 second to simulate real scenario. Integrated multidisciplinary design method is selected in order to reduce workload and time. Design variables are selected as eight which are root chord, tip chord, span, sweep and distance from the nose for the four canards and four tailfins. Multi Objective Genetic Algorithm (MOGA-II) was selected as optimization algorithm.

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