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A Review of Aerodynamic Shape Optimization for a Missile

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Abstract: Missiles are target oriented weapons with various guiding systems (Image sensors, thermal sensors, radar, inertial sensors, GPS, etc.) operating in the atmosphere, and the main purpose is to carry ammunition and strike static or moving enemy positions by the way of explosion of a warhead. Missiles were used for long distances in the past. Today, short, medium and long-range missiles are available. Missile systems are increasingly preferred because they can reach the target in a timely, faster, and accurately with the development of technology. In this paper, a review of aerodynamic shape optimization is proposed for a missile. The main aim of this article is to research and consider aerodynamic shape optimization methods that are especially used for missile aerodynamics. For this purpose, previous studies are examined to determine optimization methods that are obtained optimum geometry in terms of aerodynamic coefficients and flight performance for a missile. In this conference article, firstly, definition and aerodynamic shape optimization methods are given. The previous studies are then mentioned and classified. Lastly, the results of research of the missile aerodynamics are briefly explained for the future works.

Keywords: Missile aerodynamics, Shape optimization methods, Aerodynamic coefficients

Introduction

Aerodynamic optimizations for improving flight performance have been studied by scientists for many years. Shape optimizations improve the aerodynamic performance of the missile or any air vehicle. The aerodynamicists try to get better external geometry in terms of flight performance. Aerodynamic shape optimizations have been performed to find the shape which is optimal in that it minimizes cost function and maximize the efficiency while satisfying specified constraints. In this way, air vehicle is more efficient in terms of fuel consumption.

Missile aerodynamics concerns the air flows over the missile and investigates how the air flow effects on it in terms of drag, lift and stability. The nose, body, wing, canard and fin of missiles are designated to provide high lift to drag ratio and control. Aerodynamic shape optimization should be performed for parts of the missile (Nose, Wing, Canard, Fin, and Body) in order to achieve the mission better. (Range, Maneuverability, Speed) (Cronvich, 1983). It should have good maneuvers ability in order to reach the desired targets in the right way and to shoot the movements systems. This can be done either by controlling the wings, and/or by controlling the movements of the small fins in the tail and the canard, or by controlling all of them (canard, fin, and wing). Aerodynamic coefficients should be examined to determine whether flight performance is improved or not, when aerodynamic shape optimization is carried out. For a missile, the most important aerodynamic coefficients are drag, lift, pitching moment, yawing moment, and rolling moment. These coefficients specify the performance and stability of a missile or a moveable vehicle.

Figure 1 shows the missile that has canard, wing and tail control. Figure 2 shows the missiles which have tail control, canard control, and wing control separately.

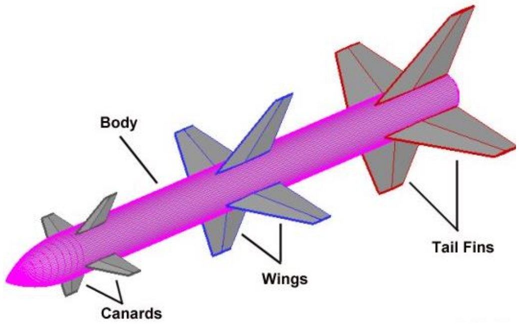


Figure 1. Major components of missile (http://www.aerospaceweb.org)

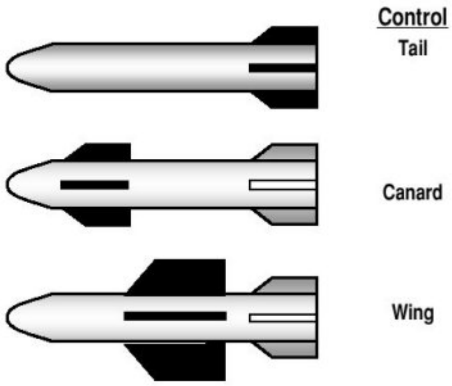


Figure 2. Three main categories of missile flight controls (Fleeman, 2001)

There are some methods that are commonly used to optimize the missile geometry in the previous studies. These are Genetic Algorithm, Adjoint Method, Discrete Sensitivity Algorithm, Particle Swarm Optimization Method, Sequential Quadratic Programming and Integrated Multidisciplinary Optimization. In addition to this, some previous studies, hybrid algorithm was also carried out. The purpose of this article; aerodynamic shape optimization methods are reviewed to determine the best optimization methods for external missile geometry in terms of flight performance.

Method of Aerodynamic Shape Optimization Classification

The following sections of the paper, the methods of the aerodynamic shape optimization that are widely used for missile are explained.

Evolutionary Algorithm

Evolutionary Algorithm is inspired by nature and solves problems through processes which simulate the behaviors of living organisms. In previous studies, many different variant of Evolutionary Algorithms (EA) are available. The principle of all Algorithm technique is similar. This technique is that a set of candidate solutions is created and some better candidates are selected to obtain next generation by applying mutation and recombination. The result of recombination, two or more new candidates are obtained and mutation is applied to one selected candidate. A set of new candidate competes with old one. This processes are continue until sufficient quality is achieved (Eiben and Smith, 2003). There are several basic types of evolutionary algorithms which are Genetic Algorithms, Evolutionary programming, Evolutionary strategies and Particle Swarm optimization. Genetic algorithm is widely used for external shape optimization of a missile.

Kachitvichyanukul (2012) was proposed a study to explain three evolutionary algorithms that are Genetic Algorithms, Particle Swarm Optimization, and differential algorithm. In this study, similarities and differences of these three optimization algorithms were observed and discussed. Figure 3 represents the flowchart of evolutionary algorithm.

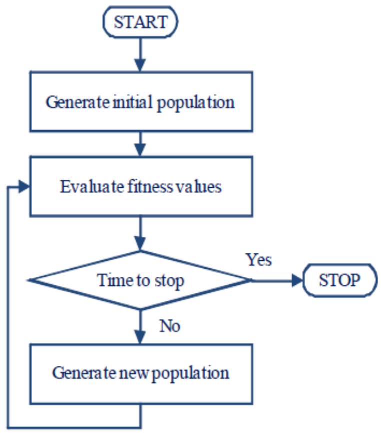


Figure 3. Flowchart of evolutionary algorithm (Kachitvichyanukul, 2012)

Genetic Algorithm

The concept of Genetic algorithm was defined by Holland (1975) in 1960s and it was described and developed by Goldberg (1989). The Genetic Algorithm and its many versions have been popular in academia and the industry mainly because of its ease of implementation and the ability to effectively solve highly nonlinear, mixed integer optimization problems (Hassan et al., 2005). Genetic Algorithm is the most popular type of Evolutionary Algorithm (EA). It is an optimization technique that is commonly used for missile aerodynamic shape optimization and involves creation function, mutation function and crossover function. New populations are attained, and the new population replace with old population using these functions. It is tried to produce good generations that are more compatible with each new generation. In this section, genetic algorithm studies that are performed for missile external geometry are mentioned.

In literature, there are several studies related with Genetic Algorithm for aerodynamic shape optimization of missile external geometry. For example, Tanıl et al. (2009) presented external configuration optimization for a missile design. In this study, MATLAB was used to perform optimization using genetic algorithm-based optimization tool. In order to consider aerodynamic coefficient of the missile, DATCOM was used. The design of the subsonic cruise missile external configuration was implemented by means of EXCON. The results of the study showed that the total of the optimized geometry was smaller than the original baseline missile. In addition to this, the mass of the missile was reduced about 30% and maneuverability was also developed by 13%. Figure 4 represents the sub-module of EXCON.

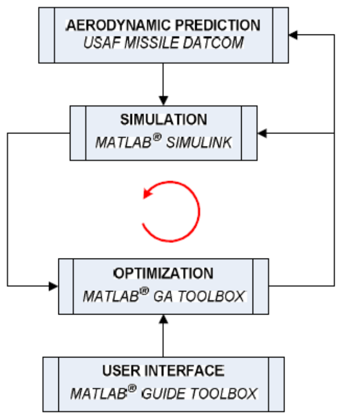


Figure 4. Sub-Modules of EXCON (Tanıl, 2009)

Dyer et al. (2012) focused on real coded Genetic algorithm to demonstrate the applicability of the aerospace engineering design. In this study, three different design studies were implemented utilizing a real coded Genetic Algorithm for single and two stage propellant missile system design and single liquid propellant missile design. Twenty-six tests were performed for these three designs. The results of the study were observed that real coded GA is useable as compared to robust binary GA. It was able to converge to a better fitness. Another optimization study using Genetic algorithm was carried out for liquid-propellant missile by Riddle et al. (2009). In this study, the entire missile design was implemented and aerodynamically optimized. Two aerodynamic prediction methods that are Aerodsn and Missile Datcom were used and the solution results were compared with each other. The results showed that the optimized missile geometry mass and flight time were decreased. However, the missile design would land 9 m and 14.3 m from target for the results of Aerodsn and Missile Datcom, respectively.

Vidanovic et al. (2017) carried out Multi-objective Genetic algorithm (MOGA) optimization for external missile configuration at different Mach numbers in supersonic flow. In order to predict the drag and lift coefficients at different Mach numbers and angle of attack, CFD solution and experimental study which was implemented in Military Technical Institute (VTI), were carried out for N1G test model and AGARD-B model configurations. The optimization results were observed that the aerodynamic efficiency was increased about 2.18%, 5.73%, 5.69% for three different Mach number (1.4, 2.3, 4), respectively. In order to maximize the range of a guided missile performing aerodynamic shape optimization, trajectory analysis and real coded adaptive range genetic algorithm were interlinked by Yang et al. (2012). In this study, canards and tailfin optimization were carried out to obtain maximum range of guided missile deriving the selected optimization method and trajectory analysis. The results of optimization study was observed that the range of the missile was increased about 5.8% for unguided flight and 21.4% for guided flight using optimal missile canard and fin shape. Figure 5 represents optimization system for a guided missile.

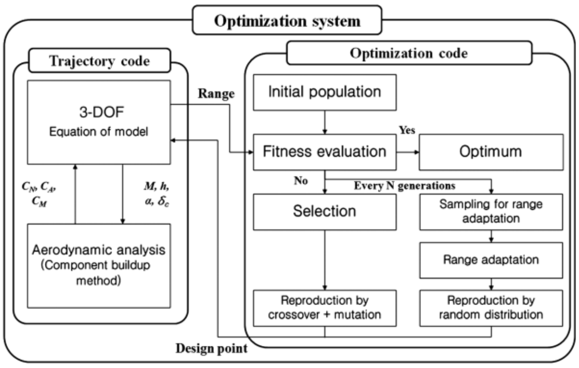


Figure 5. Range maximization system for a guided missile (Yang et al., 2012)

Nobahari et al. (2006) proposed aerodynamic shape optimization for unguided projectiles. They used two optimization methods which are Continuous Ant Colony System (CACS) and Genetic Algorithm (GA). In addition to this, to compute the normal force coefficient over flight conditions, Engineering code (EC) which combined with CACS and GA separately, was utilized. It was observed that CACS+EC gives good results compared with GA. Another similar study was carried out by Anderson et al. (2000). They focused on the shape optimization of missile aerodynamic and they used Pareto Genetic algorithm to design missile geometries for specified design goals and constraints. Hybrid design can be implemented through Pareto genetic algorithm for single or multiple-goal problems. Pareto algorithm provides diversity in the p-optimal set and this allows selecting several candidate solutions. Fin shape optimization was conducted to minimize aerodynamic heating utilizing Genetic Algorithm by Misaghian et al. (2007). They developed a code to compute aerodynamic heating of swept isolated fins and aerodynamic coefficients. Genetic Algorithm was then used to develop an optimizing program. It was observed that the drag coefficients of fins and leading edge aerodynamic heating were significantly decreased and experimental results are also good agreement with numerical results. Foster and Dulikravich (1997) presented two hybrid optimization methods, which are a gradient method based upon Rosen's projection and genetic algorithm using elements of the Nelder-Mead simplex method, to apply three-dimensional aerodynamic shape optimization of ogive-shaped, star-shaped, spiked projectiles. The results showed that the hybrid genetic algorithm was able to achieve impressive convergence according to the gradient based method. Runduo and Xiaobing (2018) proposed aerodynamic shape optimization study for long range guided rocket. In this study, aerodynamic flight characteristic program was developed using semi-empirical analysis method. Genetic algorithm was used to solve multi-objective optimization problem. CFD solution was performed to verify for optimized geometry. The end of the CFD solution was observed that maneuverability and stability were acceptable. Moreover, it was concluded that lift to drag ratio was improved and the proposed optimization method is useful.

Particle Swarm Optimization

Particle Swarm optimization (PSO) was put forward by Kennedy and Eberhart (1995). PSO is commonly used for numerical optimization problems are inspired by social behavior of bird flocking or fish schooling. PSO has some similarity with Genetic Algorithms (GA). The system is initialized with a population of random solutions and searches for optima by updating generations. However, PSO has no evolution operators such as crossover and mutation that is available Genetic Algorithms. In PSO, the potential solutions, called particles, fly through the problem space by following the current optimum particles (Ruan, 2010). PSO is more advantageous since it has better computational efficiency (less number of function evaluations) when compared with GA. In order to compare GA and PSO and show advantages of PSO, Hassan et al. (2005) proposed a study related with design optimization problems that are telescope array configuration and spacecraft reliability-based design. According to the study of Jones (2005), the evolution is performed for the best solution and the best particles give out information to others in PSO. So, the advantages of the PSO compared with GA, it is easy to implement and the adjusted parameters are less than GA. However, GA gives more precision results than PSO with respect to accuracy of model parameters. Kulkarni et al. (2015) proposed a review paper to explain and demonstrate PSO and some improved version of PSO applications for mechanical engineering. In this study, it was concluded that PSO is a very efficient and successfully applied optimization algorithm in mechanical engineering.

Usta et al. (2015) used three solution methods that are white's method, Missile DATCOM and Navier-Stokes method for prediction of aerodynamic coefficients at supersonic Mach numbers for missile fin configuration. In this study, Particle Swarm Optimization (PSO) was used to perform optimization of the missile and mesh was generated using GAMBIT and solved using Ansys Fluent. It was observed that after 67 iterations were performed, the optimum missile geometry was obtained. The pitching moment coupling was reduced on missile geometry. Figure 6 represents the PSO flowchart.

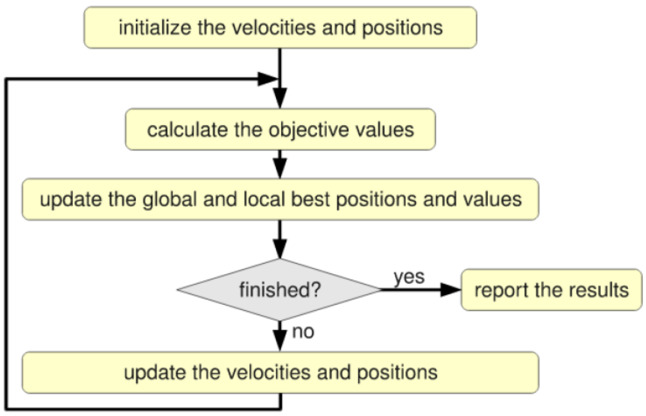


Figure 6. Flowchart of PSO (Schoene, 2011).

Xia et al. (2016) performed aerodynamic shape optimization study using PSO for supersonic launch vehicle and transonic airfoil. The results of the study were observed that the drag coefficients are reduced about % 14 and % 15 for transonic airfoil and supersonic launch vehicle, respectively.

Adjoint Method

Adjoint method is widely used for aerodynamic shape optimization in literature. This method prefers when there are a large number of design variables due to the ability to efficient compute linear design sensitivities. The Adjoint method is used for numerical optimization problem calculating the gradient function. Gradient-based methods depend on the Adjoint approach that is able to compute the objective function with respect to the design variables. For complex aerodynamic shape design problem, this approach is efficient that was shown by James (1995) since gradient information is produced.

Gradient Based Optimization

Feyzioğlu (2014) presented a shape optimization study for a missile that is free to rotate tail fins on canard controlled. In this study, asymmetric flows calculation was performed using Reynolds-Averaged Navier-Stokes

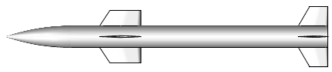
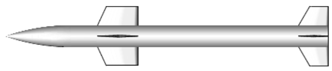
(RANS) equations in Fluent. A gradient based planform optimization was carried out to minimize the roll rate on the free to rotate tail fins. The results of the study was shown that roll rate of the optimized tail fin planform is reduced about 6% and increased the normal force about 4%.
Colonno et al. (2013) performed aerodynamic shape optimization using Adjoint-based method for fairing systems. Using a local spherical coordinate system, the fairing geometry was parameterized. Gradient-based optimization algorithms were used to obtain accurate sensitivities of aerodynamic performance.

Sequential Quadratic Programming, Integrated Multidisciplinary Optimization, and Nelder-Mead Simplex Method

Sequential Quadratic Programming method is used for nonlinear optimization problem. Multidisciplinary design optimization (MDO) uses optimization methods to solve design problems incorporating a number of disciplines. Nelder-Mead Simplex Method is used to find minimum and maximum objective function and it is widely applied numerical method and nonlinear optimization problem.

Arslan (2014) focused on missile external configurations to perform aerodynamic optimization. In order to calculate the aerodynamic coefficients, DATCOM was used. Random Search (RS) and Sequential Quadratic Programming (SQP) methods were used to perform optimization of the missile. ACRS and DONLP2 were utilized for performing each optimization application. NASA Tandem Control Missile (TCM) configuration was utilized to show whether the proposed optimization design method reached the TCM configuration in terms of aerodynamic performance. Finally, it was observed that missile external configurations could be determined by using developed optimization design method for pre-defined aerodynamic performance parameters. Table 1 represents some configuration geometries which were implemented using DONLP2, during optimization run.

Table 1. Change of geometry along optimization (Arslan, 2014)

Iteration Step	Configuration Geometry
1	
5	
15	
30	
55	
73 (Optimum Geometry)	

Lesieutre et al. (1998) carried out multidisciplinary design optimization for missile fin and configuration to improve flight performance of missile. In order to design fin planform, the developed software was used. Wind tunnel test was then performed for several missile fin planforms. Conventional and unconventional noncircular body configurations can be designed using developed method. The results of this study, fin hinge moments were minimized by means of planform optimization. Another similar study was performed multiobjective and multidisciplinary design optimization which method is called MC-MOSA, for missile and rocket by Öztürk (2009). In this study, 40 design variables were carried out to optimize the missile. It was observed that MC-MOSA is efficient and reliable.

Another shape optimization study was proposed by Cui and Yang (2010) for hypersonic arc-wing missile. They used Nelder-Mead simplex method with CFD to optimize the arc-wing and Navier-Stokes equation was used to calculate the aerodynamic performance. It was observed that Navier-Stokes and Euler solver combination showed good performance in terms of reduction of the computational cost. In order to reduce time of computation, Design of Experiment method was then utilized. The result of the study was shown that a hypersonic missile shape was higher flight performance compared with the original configuration. Figure 7 represents the flowchart of the optimization stage for this study.

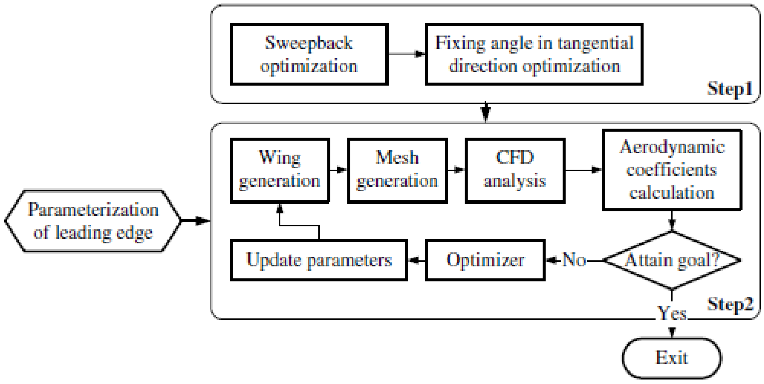


Figure 7. Flowchart of the optimization (Cui and Yang, 2010)

Lopez et al. (2014) focused on the optimization of air-ejected rocket geometries for supersonic flow field simulation that is carried out using CFD codes and simulated using OpenFOAM software. Kriging based algorithms were generated in order to perform optimization for improving geometry of missile in terms of flight performance. The end of the study, optimum design was obtained specified restrictions.

CFD simulation and wind tunnel test were conducted to obtain optimum aerodynamic shape for a guided missile by Ocokoljic et al. (2015). In order to consider optimum aerodynamic shape, the T-35 wind tunnel test was used and the tests were performed changing and improving the front part of the guided missile while the other parts of the missile remained same. The aerodynamic loads of the missile were obtained through three-dimensional Reynolds Averaged Navier-Stokes numerical simulations. Changing geometric parameters, approximately 50 missile shapes were analyzed and four parameters that were the tip chord, span, and root and wing location were examined. The results were observed that the obtained configuration was more effective than previous configuration.

Nguyen et al. (2014) presented design optimization to improve range performance based on body-wing-tail configuration for a missile. In order to eliminate small effects of design variables and specify constraints, sensitivity analysis was implemented for missile geometry. The end of the study was observed that improvement total range of the missile was 27.8% when compared with body-wing-tail configuration baseline. The aerodynamic analysis was performed using aerodynamics database (Aero DB) and tactical missile design (TDM). The optimal missile geometry was also analyzed using Ansys Fluent in order to perform validation process. Another study was performed using sensitivity analysis algorithm by Baysal and Eleshaky (1992) for scramjet-afterbody configuration. The flow analysis was compared with experimental data and it was observed that the used optimization method is more efficient than traditional methods.

An aerodynamic optimization of nose section of missile with supersonic flow was conducted by Kaleeswaran et al. (2013). Both Spherical nose cone model and Spherical model with a parabolic nose cavity were tested at same Mach speed. In this study, GAMBIT was used to design and FLUENT was used to analyze for both models. It was observed that temperature, surface pressure effects and aerodynamic drag were reduced. Parabolic nose cavity of missiles demonstrated less temperature effects compared with spherical nose cone model.

Conclusion

In this conference article a review of aerodynamic shape optimization was examined in order to determine the best methods for a missile external geometry. The end of study was observed that Genetic Algorithm and Adjoint method have been commonly used to optimize a missile external geometry. However, there is limited number of study related with hybrid algorithm and Particle Swarm Optimization in literature. After searching previous studies, it was concluded that hybrid algorithm and Particle Swarm Optimization can be studied to improve a new optimization algorithm and reach more accurate and fast solution for aerodynamic shape optimization.

Recommendations

Hybrid algorithms and Particle Swarm Optimization can be studied to perform the aerodynamic shape optimization of external missile geometry since these algorithms give fast and accurate results.

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