

Research on Multidisciplinary Integrated Design and Optimization System of Tactical Missile

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Abstract. Aiming at the problem of multidisciplinary coupling design of short-range tactical missile, an overall design model with minimum takeoff mass as the optimization objective is established. Based on the integrated design method, Aerodynamics, Motor, Mass Properties, Trajectory and other disciplines are analysed and their models are established. The multidisciplinary design optimization integration framework is constructed, and a missile multidisciplinary integrated design system is established through the program encapsulation, which can realize the coupling design and the overall parameter optimization of each sub-discipline. The system can design, analyze, simulate and optimize functions both system and subsystem, provide methods for optimization of aircraft programs and parameters, and support design schemes management in different technical states. The simulation results show that the system has obvious optimization effect and practical engineering.

1. Introduction

The overall design of the missile involves the sub-disciplines of aerodynamics, motor, trajectory, control and so on. It is a complicated systematic project. It is necessary to look for the optimal design scheme on the basis of considering the coupling of each sub-discipline. For such a complex, nonlinear and coupled system, Multidisciplinary Design Optimization (MDO) has established various models and methods[1-6] for object characteristics and has gradually become the mainstream method to solve this problem [7, 8]. However, there are some problems in the multidisciplinary optimization of aircraft, which is represented by Baker [1, 2]: the multi-disciplinary design has no user interface and the human-computer interaction is less friendly, which causes great inconvenience to users and beginners.

Firstly, this paper analyzes the aerodynamic, motor, mass properties and trajectory of the missile in the initial design stage, extracts the subject-level variables, secondly considers the coupling relationship among the sub disciplines, builds the overall optimization problem model, sets up the multidisciplinary design optimization integration framework, and finally constructs the optimization program. With the help of the UI design idea of OpenRocket[9, 10], a missile design open source software, a human-friendly interface was established and a Multidisciplinary Integrated Design (MID) system for tactical missile was established.

The MID system is targeted at the overall multidisciplinary design optimization for tactical missiles, aiming to realize the distribution, digitalization, integration, automation and visualization of the overall design process of tactical missiles. The desired effect is to improve the design quality of the missile by using the system engineering idea and adopting the appropriate systematic analysis and



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optimization strategy. Mid system aims at supporting the requirements of the tactical missile demonstration stage and plan design stage, and provides the function of the missile overall parameter rapid design, aerodynamic design, motor system design and trajectory design around the core warfare standard. It can design, analyze, simulate and optimize functions both system and subsystem, provide methods for optimization of aircraft programs and parameters, and support design schemes management in different technical states.

2. Short-range Tactical ballistic missile characteristic

Different from traditional ballistic missile, the coupling relationship between disciplines is more complicated and should be designed by MDO method in the overall optimization design of short-range tactical ballistic missile, which is embodied in the following aspects:

- From the view of range, the coupling relationship between Motor-Structure/Mass-Trajectory must be paid attention to in the overall design of short-range tactical ballistic missile.
- The trajectory characteristics of short-range tactical ballistic missiles have changed greatly with the traditional ballistic missiles, which are flying throughout the atmosphere. After the motor is finished, they can change the flight trajectory and improve the range of the missile by aerodynamic control.
- Range is not only affected by the thrust-weight ratio, but also directly affected by the missile lift-drag ratio (L/D) characteristics and ballistic design. For missile free-gliding and orbit maneuvering flight, the larger the L/D, the smaller the loss of speed for gliding and orbit maneuvering, the farther the range of gliding flight and the maneuver.

In addition, the trajectory control method and the design parameters also directly affect the trajectory angle, height and velocity of the shutdown point, and then affect the maneuvering range and the total range.

3. Integrated design

In the integrated design, the coupling between the disciplines is complex and affects each other. Therefore, we need to establish the overall design black box. Only need to change the overall parameters, through analysis and calculation, you can get the integrated design results. This integrated design includes five disciplines: geometry, aerodynamics, motor, mass and trajectory. Figure 1 is a design variable matrix of the integrated design, showing the relationship between the various disciplines. The diagonal of the matrix is the discipline analysis module, the upper-right triangular part represents the parameter transfer between the modules, and the lower-left triangle represents the optimization process. Note that the MID system is far more complex than the diagram process. The subsystem-level module setup will be shown in the following sections.

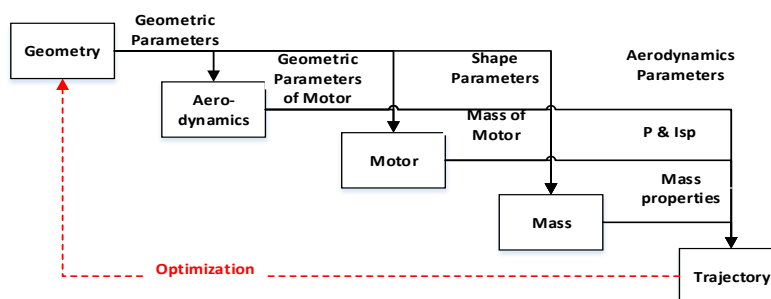


Figure 1. Relationship and optimization process of each discipline.

3.1 Geometric modeling module

The main function of the geometric module is to establish the parametric shape and provide the contour parameters to the downstream disciplines such as aerodynamics, motor and mass. MID

provides a visual geometric design interface that enables the autonomous selection of missile components such as nose cones, bodies, interstage segments, and wing flaps. The parameters of each part can be modified freely, the modified model will be displayed in the interface in real time, the model can choose a variety of view modes: Face, Side, 3D sketch, 3D diagram. Mid system provides a rich variety of missile components to add models. The bodies and internal loads can be changed arbitrarily, and the center of mass (CG) and the center of pressure (CP) are calculated in real time. For example, there are 6 choices for the nose curve: Conic, Ogive, Ellipsoid, Power, Haack and Parabolic. Meanwhile, wings can set any number, shape and thickness.

In this paper, parameters which can significantly change the shape of the missile and affect the aerodynamic performance of the missile are selected, such as missile diameter D , missile slenderness ratio λ_B , one cone slenderness ratio λ_{l1} , two cone slenderness ratio λ_{l2} , and columnar length slenderness ratio λ_{lc} . Based on parametric modeling method, a series of shapes shown in Figure 2 can be obtained by changing the above parameters.

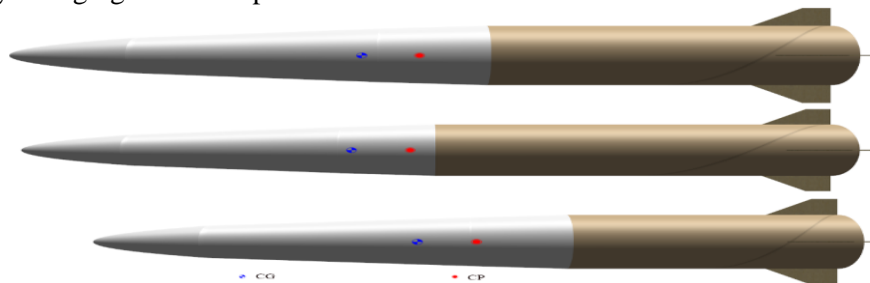


Figure 2. Example of 3D sketch based on parametric shape.

3.2 Aerodynamic modeling module

Missile Datcom 1997 is an engineering aerodynamic estimation software developed by the United States Air Force to collect flight test data of a large number of missiles in the United States, suitable for conventional layout missiles. The aerodynamics module integrates the Missile Datcom into the MID and converts the parameterized shape, the Mach number (Mach), the angle of attack (AoA) and the height (H) into the input of the Missile Datcom, makes an aerodynamics table by calculating the parameters of the lift & drag coefficient (Cl & Cd) and CP. The length of the missile and the change of the different section diameters are described by the missile's outline, the wing part needs the positioning dimension, number, type, plane shape and the mounting position of the wing.

Figure 3 shows the operation of the aerodynamics module in the MID system. Figure 3(a) is set for 005.dat input file, the appearance parameters and Mach, AoA and H are set by visual operation to generate the file, the generated for 005.dat and the output file for 006.dat calculated by Datcom can be displayed on Figure 3(b). The module can also show the calculated aerodynamic table and draw it.

No.	Mach	AoA	H
1	0.1	0	50,000
2	1.41	2.63	50,000
3	2.72	5.26	50,000
4	4.03	7.89	50,000
5	5.34	10.53	50,000
6	6.65	13.16	50,000
7	7.96	15.79	50,000
8	9.27	18.42	50,000
9	10.58	21.05	50,000
10	11.89	23.68	50,000
11	13.21	26.32	50,000
12	14.52	28.95	50,000
13	15.83	31.58	50,000
14	17.14	34.21	50,000
15	18.45	36.84	50,000
16	19.76	39.47	50,000
17	21.07	42.11	50,000
18	22.38	44.74	50,000
19	23.69	47.37	50,000
20	25	50	50,000

(a) Flight parameters

Input	Output
<pre> DIM M DERIV DEG \$FLTCN MALPHA=20., NMACH=20., MACH=0. 1, 1. 41, 2. 72, 4. 03, 5. 34, 6. 65, 7. 96, MACH(8)=9. 27, 10. 58, 11. 89, 13. 21, 14. 52, 15. 83, MACH(14)=17. 14, 18. 45, 19. 76, 21. 07, 22. 38, MACH(19)=23. 69, 25., ALPHA=0., 2. 63, 5. 26, 7. 89, 10. 53, 13. 16, 15. 79, ALPHA(8)=18. 42, 21. 05, 23. 68, 26. 32, 28. 95, ALPHA(13)=31. 58, 34. 21, 36. 84, 39. 47, 42. 11, ALPHA(18)=44. 74, 47. 37, 50., ALI=50000., 50000., 50000., 50000., 50000., ALI(6)=50000., 50000., 50000., 50000., 50000., ALI(11)=50000., 50000., 50000., 50000., ALI(15)=50000., 50000., 50000., 50000., 50000., ALI(20)=50000., \$SREFQ SREF=1., LREF=1., \$ \$AXIBOD NX=17., X=0. 0, 0. 226, 0. 452, 0. 678, 0. 904, 1. 13, 1. 56, 1. 99, 2. 42, 2. 85, X(11)=3. 28, 3. 47, 3. 66, 3. 85, 4. 04, 4. 23, 7. 28, R=0. 0, 0. 134, 0. 19, 0. 232, 0. 268, 0. 3, 0. 33, 0. 36, 0. 39, 0. 42, R(11)=0. 45, 0. 46, 0. 47, 0. 48, 0. 49, 0. 5, 0. 5, TRUNC=. FALSE., DEXII=0., \$ \$FINSET1 SSPAN=0., 0. 3, CHORD=0. 7, 0. 25, PHIF=0., 90., 180., 270., XLE=6. 58, 6. 580. 7, SWEEP=0. 983, STA=0. 0, NPANEL=4., \$ \$PROIUE NPROI=0., PIIY= XPROI= NLOC= LPROI= WPROI= HPROI= OPROI=\$ SOSE DAMP PRINT GEOM BODY BUILD PLOT NEXT CASE </pre>	

(b) Generated for005.dat

Figure 3. Calculation process of aerodynamics module.

3.3 Motor calculation module

The function of motor calculation module is to calculate motor parameters such as motor mass, thrust and specific impulse, which is provided to trajectory module. MID embedded a variety of engine design methods: a) Produce thrust curve by manual selecting points, b) Embedded solid rocket motor interior ballistic performance calculation module, the motor can be detailed design.

The theoretical specific impulse of the solid motor is calculated by the theoretical extrapolation formula. When interpolating, the influences of nozzle expansion ratio and the pressure in the combustion chamber are considered. On the basis of thermodynamic calculation, extrapolation formula[11] can be used.

$$I_{sh} = 2408 \times \sqrt{0.3189 + 0.4187 \ln \varepsilon - 0.0279 \ln^2 \varepsilon} \times (0.9914 + 0.044 \ln p_c) + 522.0226 p_c^{0.006965} \cdot \varepsilon^{-0.3351} - 1557.6 p_c^{-0.9930} \cdot \varepsilon \cdot p_a \quad (1)$$

In formula (1), ε represents the nozzle expansion ratio, p_a (MPa) represents the ambient pressure, p_c (MPa) represents the combustion chamber pressure.

The results of the extrapolation formula are not more than 0.1% relative to the thermodynamic calculation. At the same time, the actual specific impulse is also calculated by the SPP empirical formula[12] Motor mass analysis includes charge mass, shell mass and nozzle mass.

3.4 Mass calculation module

Through the parameters provided by the Geometry and Motor disciplines, the total mass is calculated and provided to the trajectory discipline. MID provides a detailed calculation of quality features. The internal components and load parts of the missile can be visually configured, such as engine, main load, parachute, etc. At the same time these components will be included calculation of the center of mass and mass properties. Figure 4 shows the visualization of the engine, warhead and missile-borne equipment by the 3D diagram. MID also shows CG and CP of the missile.

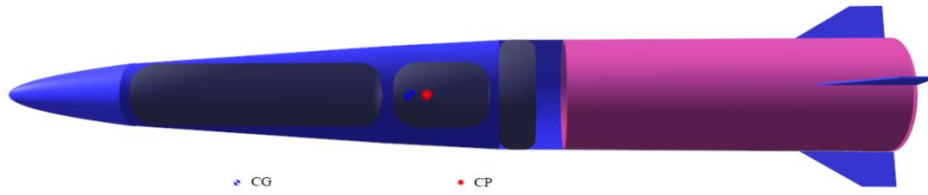


Figure 4. Visual layout of missile-borne equipment.

To simplify processing, Mass disciplines is divided into three parts: the shell mass, payload mass, motor mass.

$$m_0 = m_{shell} + m_{load} + m_{eng} \quad (2)$$

In formula (2), m_0 represents the total mass, m_{shell} represents the quality of the shell, simplified by pimping shell, m_{load} represents motor quality, including motor charge quality, shell quality and nozzle quality, m_{eng} represents payload quality, including warhead quality, missile-borne equipment quality, and other constant quality.

3.5 Trajectory calculation module

The range is calculated from the various parameters provided by the above four disciplines. MID can provide many different trajectory modes. The concrete trajectory model is realized by changing the AoA command or the engine model, AoA command and ballistic parameters are also visualized. It is supported to calculate different types of trajectory at the same time, which is easy to compare overall parameters.

A 3DOF ballistic equation without considering the Earth's rotation and flat rate is used to compute the standard ballistic trajectory[13]. The kinetic equation and kinematics equation are as follows.

$$\begin{aligned} m \frac{d^2 \vec{r}}{dt^2} &= \vec{P} + \vec{R} + \vec{F}_c + m \vec{g} + \vec{F}_k \\ \frac{d\vec{r}}{dt} &= \vec{v} \end{aligned} \quad (3)$$

In formula (3), \vec{P} represents the thrust vector of the motor, \vec{R} represents the aerodynamic vector, \vec{F}_c represents the control force vector, \vec{F}_k represents the Gothic force vector and $m \vec{g}$ represents the gravitational vector.

3.6 Multidisciplinary integration

The construction process of the above modules has been clearly stated. Based on multidisciplinary integration technology, the above modules are integrated into MID system, and suitable optimization algorithms are used to optimize multidisciplinary design.

4. Multidisciplinary optimization example of tactical missile overall performance

Tactical missile multidisciplinary optimization is based on the establishment of the geometry, aerodynamics, mass, trajectory of the discipline model, through appropriate optimization algorithm, to obtain the result that can make the overall performance of tactical missile optimal. In the optimization of the overall performance of tactical missiles, optimization problems usually aim at the optimization of take-off mass m_0 , and the size and the range R are reduced to the desired effect.

That is to take the overall parameters design of a short-range tactical missile for the study, requiring the design of a vertical launch and without control of the single-stage short-range tactical missiles, and range is not less than R_0 . The design target is the minimum m_0 . Missile diameter D is not optimized. The optimization problem is to ensure that the missile can reduce its m_0 and missile length under the premise of meeting certain range requirements.

4.1 Multidisciplinary Optimization Model

Multidisciplinary design model is the synthesis of discipline design model, which needs to establish the objective function, constraint condition and design variable of the whole system. Design variables play a crucial role in multidisciplinary design. The interaction of design variables among different sub-disciplines reflects the coupling and influence between different sub-disciplines.

In multidisciplinary design, design variables need to be unified, not only in the discipline-level design variables, but also in system-level design variables. These system-level design variables are coupled variables that are part of the discipline-level design variables and are responsible for interacting with other disciplines and playing a decisive role throughout the optimization process.

The principle of choosing a design variable is to express the content of the sub-discipline as completely as possible with as few variables as possible.

According to the above design variable selection principle, the design variables shown in Table 1 are selected, and the system-level design variables are arranged according to the sensitivity. The sensitivity of each design variable to m_0 is shown in Figure 5. The sensitivity of design variables indicates that the change of design variables can cause the drastic degree of change when the m_0 is the optimal target. The sensitivity of each design variable was calculated using the Full Factorial Design of Experiments, which can accurately assess the effect of the factor on the coupling effect.

Table 1. All design variables

NO.	Variable	Description	Notes
1	t	Motor working time	system-level (motor)
2	p_c	Combustion chamber pressure	system-level (motor)
3	D	Missile diameter (motor diameter)	system-level (motor, aerodynamics)
4	ε	Nozzle expansion ratio	system-level (motor)
5	λ_B	slenderness ratio	system-level (aerodynamics)
6	λ_{l2}	Two cone length ratio	system-level (aerodynamics)
7	λ_{l1}	One cone length ratio	system-level (aerodynamics)
8	λ_{LE}	Motor slenderness ratio	discipline-level(motor)
9	λ_{lc}	Column length ratio	discipline-level (aerodynamics)
10	m_{eng}	Motor mass	discipline-level (mass)
11	S_{body}	Missile surface area	discipline-level (mass)
12	m_0	Take-off mass	discipline-level (mass)
13	R	Range	discipline-level (trajectory)

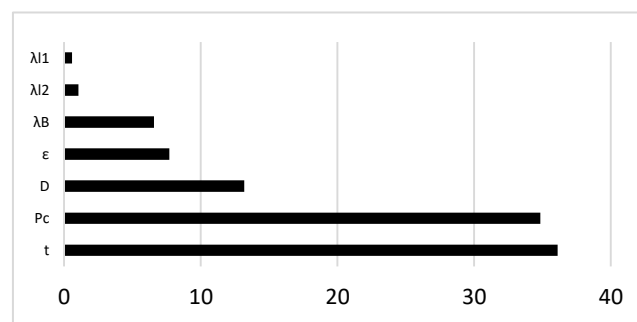


Figure 5.System-level design variable sensitivity

In this paper, in order to improve the efficiency of integrated design, part of the design parameters will be cured, such as the size of the wing, the motor shell material and charge, the missile shell material. At the same time, according to the sensitivity analysis of each design variable, 13 design variables shown in Table 1 are selected finally, of which the first 7 are optimized as system-level design variables and the latter 6 discipline-level design variables are derived from system-level design

variables, which play a binding role in the process of optimization. Through the solidification of the design parameters and these design variables, the integrated design of the missile's overall parameters of the aerodynamic, motor, mass, trajectory and other disciplines can be described.

Due to the limitations of practical problems, design variables need to select a certain range of values, variables that beyond the scope of the value of the design should be discarded.

As a multiple constrained single target optimization problem, the optimization problem can be described as follows:

$$\begin{aligned}
 & \min m_0(X) \\
 & X = (t, p_c, D, \varepsilon, \lambda_B, \lambda_{\eta_1}, \lambda_{\eta_2}) \\
 & s.t. \quad R \geq R_0, \\
 & \quad \lambda_{\eta_{c \min}} \leq \lambda_{\eta_c} \leq \lambda_{\eta_{c \max}}, \\
 & \quad \lambda_{LE \min} \leq \lambda_{LE} \leq \lambda_{LE \max}.
 \end{aligned} \tag{4}$$

In formula (4), R_0 represents the minimum range constraint, $\lambda_{\eta_{c \min}}$ and $\lambda_{\eta_{c \max}}$ represent the upper and lower bounds of column length ratio, $\lambda_{LE \min}$ and $\lambda_{LE \max}$ represent the upper and lower bounds of motor slenderness ratio.

4.2 Optimization Methods

MID system has several methods in place for users to optimize. In this paper, Gradient Optimizer (the gradient optimization method) is adopted to optimize. Gradient optimization method has the characteristics of small calculation, short optimization time and good calculation effect. Although gradient optimization does not necessarily converge to the global optimum, in engineering practice, the local optimal point has already satisfy the actual engineering requirements.

4.3 Optimization Examples and results

A missile's baseline shape for $D=1000mm$, $\lambda_B=6.3$, $m_0=4176kg$, $R=360km$. Specific constraints for $R \geq 350km$, $0.35 \leq \lambda_{\eta_c} \leq 0.65$, $2 \leq \lambda_{LE} \leq 5$.

Optimized with MID system, spends a shorter time of 45min., m_0 is reduced by 22.25% under the precondition of satisfying the design requirement, and the optimization effect is remarkable.

Table 2 lists the optimization results of the missile's overall parameters. It can be seen that m_0 decreases significantly under the precondition of satisfying various constraints. Due to λ_B , λ_{LE} and λ_{η_c} decreases, m_{shell} and m_{eng} both are reduced, and m_{load} as constants remain unchanged, so m_0 decreases. At the same time, decrease of m_{eng} leads to t decrease, p_c and ε both increase and direct result is F (Thrust) increased to meet the predetermined requirement of range. According to the above analysis, the optimization result is reasonable and usable.

Table 2. Optimization results of missile overall parameters

Variable	Initial Value	Value Range	Optimal
m_0 / kg	4176	-	3416
R / km	360	-	352
λ_B	6.3	[4,10]	6.1229
λ_{η_1}	0.087	[0.05,0.15]	0.0847
λ_{η_2}	0.389	[0.3,0.5]	0.4255
λ_{LE}	2.3	[2,5]	2
p_c / kPa	6	[4,10]	7.8435
t / s	57	[40,80]	41
ε	4	[3,10]	10
F / kN	109.5	-	130.1

MID system can visualize the comparison of the results before and after the optimization. Figure 6 graphically shows the shape change of the missile before and after optimization. You can see clearly that λ_B and λ_{lc} are reduced.

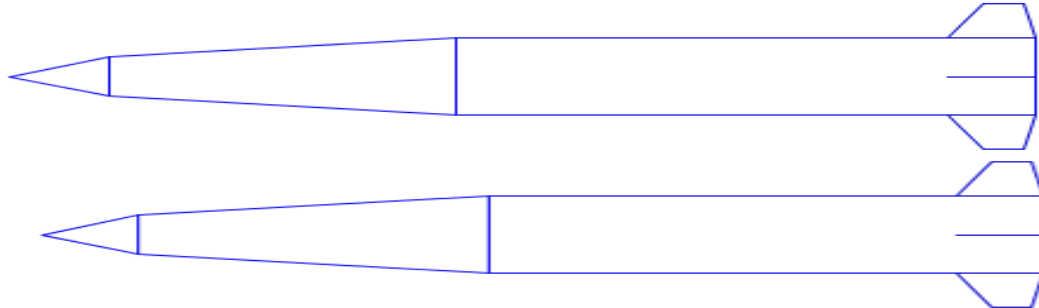


Figure 6. Comparison of missile profiles before and after optimization

5. Conclusions

In this paper, MID system with human-machine friendly operation interface is built with the help of MDO idea and integrated design method. Through the overall preliminary design and optimization of single-stage solid-motor short-range tactical ballistic missiles, MID system shows its rich operability and engineering practicability. The overall preliminary design takes less time and achieves the desired optimization effect. It shows that the integrated design model and MID system are effective under certain conditions, and can be used in the overall preliminary design of engineering practice. Mid, as an effective tool in the overall preliminary design stage of tactical missile, will greatly reduce the R&D time, improve the design efficiency, and help the missile designers to meet the demand of war standard and improve the design quality of the missile.

To further improve the generality of mid, the next research work mainly includes: refining the aircraft parametric shape, increasing the optimization algorithm, integrating more discipline design modules. To solve the problem of the current overall optimization module.

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