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Research of Multidisciplinary Optimization of ISFS Based on Collaborative Optimization

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Abstract: Individual-soldier firepower system includes several subsystems, and the relationships of competition and coupling exist in each subsystem. In order to obtain the optimal performance of the entire system, the multidisciplinary optimization is employed in this paper. The recoil force is taken as the objective function, and the performances of weapon dynamics, internal ballistics, external ballistics and terminal effects are taken as the subsystems. To establish the multidisciplinary optimization model of individual-soldier firepower system, the collaborative optimization method is adopted. And then, for optimizing the complicated system globally, the parallel, global and local optimization methods, response surface methodology, and subsystem models are used to carry out the optimization computation on the basis of considering the coupling relationships of each sub-discipline. The computational results shown that, the multidisciplinary optimization of individual-soldier firepower system can not only ensure the performances of internal ballistics, external ballistics and terminal ballistics, but also further optimize the recoil force.

Keywords: Collaborative optimization, individual-soldier firepower system, multidisciplinary optimization, response surface method, weapon.

1. INTRODUCTION

In the engineering practice, there is coupling relationship between systems. It is hard to optimize the complex mechanical system. The traditional design or conventional optimization method is to establish multi-objective optimal model. Because of the competing relationship between each objective function of multi-objective optimization problems, the improvement of the optimization effect for one objective function is at the cost of the optimization effect degradation of other objective function. It is hard to get the optimum solution [1-3].

In order to solve the above problems, people have done a lot of research and experiments in multidisciplinary design optimization. They want to get the overall optimal solution of complex systems, such as Balling first use the multidisciplinary optimization (MDO) method to solve multi-objective optimization problems and successfully use collaborative optimization to the multi-objective optimization problem. The reference [4] makes the collaborative optimization between the simulated annealing algorithm and the NLPQL. It uses the idea of dynamic relaxation and explains the reliability and stability of this method by the experiment of gear reducer. The reference [5] suggests a MDO problem description method based on subject relationship matrix. It regards the input/output variables of regular subjects as basic interface and defines the coupling relationship between disciplines by subject relationship matrix. It can sustain the automatic identification of MDO variable types and the automatic parsing of the coupling data flows. The reference [6] combines collaborative optimization with global multi-objective optimization algorithm. It establishes satellite structural dynamic multi-objective collaborative optimization model for the multi-objective constraint, time-consuming structural optimization problems in satellite system. After solving this problem, the multiple targets of satellite can get a larger degree of optimization. The reference [7] use the response surface approximation model and combine sequential quadratic programming with multipurpose optimal method based on adaptive weighted to make the multidisciplinary collaborative optimization of body structure. It guarantees the goals of vehicle lightweight and significantly improves crash safety of body side. The reference [8, 9] applies MDO to ships and gets a better optimization effect.

Multi-disciplinary design optimization (MDO) can effectively solve the coupling relationship between systems. The design optimization of each system can make concurrent design by the coordinate with each other of design variables.

In the complex multi-body system, the optimum structural design is a necessary technology. The optimum structural of individual-soldier firepower system (ISFS) is a complex work. It applies the quality of light and the high demandingness of strength, stiffness, dynamic and thermodynamic performance. It is becoming more important to make the optimization design of ISFS.

2. THE INTRODUCTION OF MDO

MDO [10] is optimization method born of theory of large scale systems. It has the characteristic to analyze complex systems composed by coupling of multiple disciplines or subsystem. In the entire design process of complex systems, it thinks full of the influence of interaction among various disciplines. It use distributed computing technology to integrate disciplinary knowledge. According to the idea of design-oriented, it integrates model and analysis tool of model and analysis tool. It manages the design process by effective design and optimization strategy. The design can get the overall optimal solution and keep the autonomy of each system [11].

The research contents of MDO can divide into theoretical method and supporting platform. Its specific include: the systematic mathematical modeling, system decomposition technique, optimization framework, optimizing solution strategy, approximate method, sensitivity analysis of the system, structure and the system integration platform and so on. The theoretical method provides theoretical support for MDO. The supporting platform provides application environment for the research of theory. The theoretical method and supporting platform supply each other and get the joint development.

2.1. The Mathematic Model of MDO

The premise of MDO is to establish interdisciplinary mathematical model. Before the MDO of complex system, it is first to accurately establish the optimization model of complicated products by mathematical description way. It means that establish the mathematical modeling of MDO. Only accurately establish the mathematical modeling of MDO, can it exactly solves the problem. The primary task of MDO is to establish mathematic model. The general mathematical expression of MDO is shown in equation (1). For the design of detailed product, it establish mathematical model of the specific system by direct at the specific MDO problem [12].

$$\begin{cases} find: x \\ \min: f = f(x,y) \\ s.t. \begin{cases} g_i(x,y) \le 0 & (i = 1,2,3,\cdots,m) \\ h_i(x,y) = 0 & (i = 1,2,3,\cdots n) \end{cases} \end{cases} \tag{1}$$

In Eq. 1, f is the objective function; x is the design variable; y is the state variable; $g_i(x,y)$ is the inequality constraints; $h_i(x,y)$ is the equality constraint; m,n are the number of constraint type.

2.2. MDO Method

MDO method is the core problem of multidisciplinary design optimization and use the optimize structure for concrete issue. At the moment, the MDO method divides into single stage optimization method and two-stage optimization method. The single stage optimization method includes: Multidisciplinary Feasible Method-MDF, Simultaeous Analysis and Desigh, Individual Discipline Feasible Method-IDF. The two-stage optimization method includes: Concurrent Subspace Optimization-CSSO, Collaborative Optimization-CO and Bi-Level Integrated System Synthesis-BLISS. The Collaborative Optimization-CO and Concurrent Subspace Optimization-CSSO are the algorithms of more research [13].

2.2.1. Collaborative Optimization

The Collaborative Optimization (CO) is a kind of two-level optimization, includes: system-level and subsystem level. The **CO** put state variable into design variable by using the idea of IDF. It relieves the coupling relationship of each discipline and makes the subsystem level optimization become subsystem level optimization. The method is that system-level distribute the target of system variables to subsystem level. Each of the subsystem level meets their constraint. The objective function minimizes the gap of the system coupling variables and distributive target value. After the design of subsystem level, each objective function returns to system-level and form the consistency constraint of system-level. It optimizes the system-level at last. By several times optimized iterative computations between system-level and subsystem level, the CO get the system optimal solution. When the size of the optimization problem enlarged, because of the solver or optimizer of subsystem level, the CO parallel optimization method is not sensitive as MDF. So the CO method is fit for multidisciplinary design optimization problem of large-scale complex engineering system [14].

2.2.2. CO Mathematic Model

This text design Z as the system level design variables, it includes the system level design variables, use Z_{XSYS} to show(distribute design variable into subsystem level A、B, shown X_{UA}, X_{UB}) the coupling state variables (shown Z_{YA}, Z_{YB}) , system level objective function F (Z (Z_{XSYS}, Z_{YA}, Z_{YB})), constraint condition Ji (Z), the subsystem number i. Take two subsystems for example, the mathematical model of optimization as follows:

system-level:

$$\begin{cases} Min. \quad F(Z_{XSYS,} Z_{YA,} Z_{YB}) \\ s.t. \quad J_1(Z_{XSYS,} Z_{YA,} Z_{YB}) = |X_{SYSA} - Z_{XSYSA}|^2 + |Y_A - Z_{YA}|^2 + |Y_B - Z_{YB}|^2 = 0 \\ \qquad J_2(Z_{XSYS,} Z_{YA,} Z_{YB}) = |X_{SYSB} - Z_{XSYSB}|^2 + |Y_A - Z_{YA}|^2 + |Y_B - Z_{YB}|^2 = 0 \end{cases} \tag{2}$$

subsystem level:

subsystem A:

$$\begin{cases} Min. \quad J_1(X_{UA}, Y_B) = |X_{SYSA} - Z_{XSYSA}|^2 + |Y_A - Z_{YA}|^2 + |Y_B - Z_{YB}|^2 \\ s.t. \quad g_{A1}(X_{UA}, Y_B) \le 0 \\ \qquad g_{A2}(X_{UA}, Y_B) \le 0 \end{cases} \tag{3}$$

subsystem B:

$$\begin{cases} Min. \quad J_1(X_{UA}, Y_B) = |X_{SYSA} - Z_{XSYSA}|^2 + |Y_A - Z_{YA}|^2 + |Y_B - Z_{YB}|^2 \\ s.t. \quad g_{B1}(X_{UA}, Y_B) \le 0 \\ \qquad g_{B2}(X_{UA}, Y_B) \le 0 \end{cases} \tag{4}$$

The collaborative optimization method weakens the processing of system design variables and coupling variable. It gives sufficient autonomy to interdisciplinary design problems. On condition of guarantee the consistency between the discipline constraint and the target system layer, we can no considering the influence of other disciplines and independently design. It avoids the influence of other subject. It decreases the highest order of the subsystem level optimization objective function and avoids the difficulties to solve high order nonlinear equation or equations. But, it enlarges the dimensions of the design variables because it regards the state variables as design variables. The expression of the system level optimization problem leads to the difficulty of the system level optimization.

3. INTERDISCIPLINARY MODEL OF ISFS

In front of the multidisciplinary design optimization, it should divide systems into several subsystems by different ways. The way to divide the system is importance and it decides the complexity of the system to solve and the convergence rate of the solution. There are two ways to divide the system. One way is to divide the subsystem by subject and the other hand is according to the closing heavy piece. The ISFS can divide into four subsystems which include: external and internal ballistic trajectory, terminal efficiency and weapon dynamics.

3.1. The Internal Ballistic Model

$$\begin{cases} \psi = \chi z(1+\lambda z+\mu z^2) \\ \dfrac{dz}{dt} = \dfrac{p}{I_k} \\ Sp = \varphi m \dfrac{dv}{dt} \\ p[V+V_0-\dfrac{\omega}{\gamma}(1-\psi)-\alpha\omega\psi] = f\omega\psi - \dfrac{\theta}{2}\varphi m v^2 \\ \dfrac{dl}{dt} = v \end{cases} \tag{5}$$

In the formula, the meanings of parameters refer to the reference [15].

3.2. Outside Ballistic Model

$$\begin{cases} \dfrac{dv_x}{dt} = -cH(y)G(v)v_x \\ \dfrac{dv_y}{dt} = -cH(y)G(v)v_y - g \\ \dfrac{dx}{dt} = v_x; \qquad \dfrac{dy}{dt} = v_y \\ v = \sqrt{v_x{}^2 + v_y{}^2} \\ \dfrac{d}{dt}(J_\xi \dot{\gamma}) = -M_{xz} \\ \dfrac{dn}{dt} = \dfrac{\dot{\gamma}}{2\pi} \end{cases} \tag{6}$$

In the formula, the meanings of parameters refer to the reference [16].

3.3. Terminal Efficiency Model

$$\begin{cases} P_m = 1 - \prod_{i=1}^{m}\left(1 - P_{(N,i)}\right) \\ P_s = P(x,y) = 1 - e^{-\overline{m}\cdot\overline{p}_{hk}} \\ \quad = 1 - e^{-\overline{N}_s} = 1 - e^{-a_s(x,y)s_n} \\ P_{sjz} = p_m \cdot p_s \\ s = \int_{-\infty}^{+\infty}\int_{-\infty}^{+\infty} P(x,y) d_x d_y \end{cases} \tag{7}$$

In the formula, $p_{(N,i)}$ is bomb fragments hit probability; P_m is hit probability of hit the target m fragment; P_s is kill probability; P_{sjz} is grenade firing efficiency; S is all the lethal area.

3.4. Dynamic Model of Weapon

It establishes weapon dynamics simulation model and simulation data on the ADAMS virtual prototype simulation platform, as shown in reference [17].

4. MDO RESEARCH OF ISFS

4.1. MDO Modeling of ISFS

The main parameter name and symbol definition of ISFS, as shown in Table **1**:

For the ISFS, weapons designers want to get the small recoil and light weapon weight. The two indexes are important indicators of armament design.

Such as the grenade launch part of ISFS, the system level optimization goal is to get the minimum recoil. It regards the factors of affect weapon recoil as the design variable. With certain constraint condition, it puts forward a collaborative optimization model of two-stage optimization which puts interior ballistic, exterior ballistic, ballistic end, automata dynamics as the four subsystem and the model is the system optimization goal.

Such as the optimization objective of minimum recoil, we can describe the system level optimization model of ISFS shown as follows:

Find Z∈ (lgsys, mdwsys, $v_0$sys, vcsys, theta0sys, thetacsys, Jndd, Jwdd, Jzddd, Jwuqi)

Min. D(Z)=force

s.t $0.085kg \le mdwsys \le 0.095kg$;

$0.36m \le \lg sys \le 0.42m$;

$210m/s \le v0sys \le 260m/s$;

$120m/s \le vcsys \le 300m/s$;

$0° \le theta0sys \le 10°$;

$0rad \le thetacsys \le 0.8rad$; $x = 800m$;

$Jndd, Jwdd, Jzddd, Jwuqi < 0.00001$

The said parameters of –sys is system level parameter.

Subsystem level model:

(1) Internal trajectory calculate subsystem mathematic model

Table 1. Main parameters table of fire subsystem optimization.

Name of Parameter	Units	Symbols	Names of Parameter	Units	Symbols
quality of the projectile	kg	*mdw*	range	m	*X*
medicine chamber volume	m^3	*vys*	recoil	N	*force*
ladung	kg	*wzy*	the projectile average wall thickness	m	*T0*
the maximum bore pressure	MPa	P_0	lethal area	m^2	*area*
the projectile muzzle velocity	m/s	V_0	shell quality	kg	G_0
the quality of the barrel	kg	*mqg*	explosive quality	kg	*W*
recoil spring rigidity	N	*phzh*	shrapnel shrapnel angle	radian	*thetac*
recoil spring severity	N/m	*khzh*	barrel length	m	*lg*
The barrel spring precompression	N	*pqgh*	bolt recoil spring rigidity	N/m	*khc*
the barrel spring severity	N/m	*kqgh*	bolt recoil spring precompression	N	*phc*
initial beam angle	°	*Theta0*	pill placement speed	m/s	*vc*
automaton quality	kg	*mzdj*			

The design of internal trajectory is the base of armament design. The energy for gun to work properly is root in the combustion pressure of chamber gunpowder, so the internal trajectory is an important link in the entire gun design. The design of internal trajectory is on the basis of weapons caliber, projectile velocity and initial velocity of outside ballistic design. With the selection of bore pressure, chamber enlargement coefficient, powder shape and properties, it calculates structured data such as the medicine chamber volume and length of barrel and get the loading conditions data such as the charge and the thickness of medicine granule.

Find $X_1 \in (vys, wzy, lg, mdw, V_0, P_0)$

Min $\mathrm{Jndd}(X_1) = |(\mathrm{lg} - \mathrm{lgsys})/\mathrm{Lg}|^2 + |(\mathrm{v0} - \mathrm{v0}sys)/\mathrm{v0}|^2 + |(mdw - mdwsys)/mdw|^2$ s.t $80MPa \le P0 \le 300MPa$

(2) External ballistics subsystem mathematic model

The design of external ballistics is the base of certain tactical technical requirements and the tactical tasks. It considers the requirements of meet the mobility in different degrees and other natures and regards power requirements as the constraint and confirms reasonable diameter, velocity and warhead weight. It can get the reasonable ballistic scheme. According to small grenade characteristics and the main combat mission, it is an important nature for pills accurately fly to the target.

Find $X_2 \in (v0, theta0, thetac, mdw, vc, X, t)$

Min $Jwdd(X_2) = |(\mathrm{mdw} - \mathrm{mdwsys})/\mathrm{mdw}|^2 + |(v0 - v0sys)/v0_0|^2 + |(vc - vcsys)/vc|^2$ s.t $X = 800m$

(3) Terminal lethality subsystem mathematic model

Find $X_3 \in (H, W, T_0, thetac, vc, Wzy, area)$

Min $\mathrm{Jzddd}(X_3) = |(\mathrm{vc - vcsys})/\mathrm{vc}|^2 + |(\mathrm{thetac - thetacsys})/thetac|^2$

s.t $115m^2 \le area \le 400m^2$

(4) Weapon dynamics subsystem mathematic model

The design of weapons automata determines the common work of radio frequency weapons and ammunition. It requires a certain radio frequency f and reducing recoil force. The analysis module directly uses the simulation code of many-body dynamics.

Find $X_4 \in (mqg, ,mzdj, kqgh, pqgh, khc, phc, khzh, chzh, vqg, mqq)$

Min $Jwuqi(X_4) = |(\mathrm{mdw - mdwsys})/\mathrm{mdw}|^2 + |(\mathrm{lg - lgsys})/\mathrm{lg}|^2$

s.t $Mz \le 4kg$

4.2. The Example

In multidisciplinary design optimization, the system level of constraint function *Ji* has no direct connection with system-level design variables. The constraint functions may be smooth, even is discontinuous, but also can bring the problem of virtual local optimal point and so as to make the poor robustness of collaborative optimization method. Therefore, it uses the global optimization algorithms such as simulated annealing algorithm and genetic algorithm to improve the robustness of collaborative optimization method and local search algorithm to improve the local search ability.

Based on the optimization model of the cooperation and from the perspective of global and design, it uses parallel, global optimization algorithm and local optimization search strategy by using the response surface model approximation of system and subsystem level model. It regards minimum damage area of 115 square meters and 800 meters range as constraint and minimum recoil as fire subsystem optimization goal to calculate. In optimization design, the design space is irregular. If only by the optimization method based

Table 2. Part optimization results of the target of recoil.

Parameters	Optimal Value	Parameters	Optimal Value
mdw/kg	0.089	*X*/m	800
vys/ m^3	2.504e-6	*force*/	59.8
wzy/kg	0.00117	*T0*/m	0.00204
G0/kg	0.0467	*Xc/m*	0.0297
P_0/MPa	86	*sare*/m^2	128
V_0/ $m\cdot s^{-1}$	219	*theta0*/°	6.4
mqg/kg	0.503	*W*/kg	0.0139
phzh/N	70.8	*thetac*/rad	0.1407
khzh/ $N\cdot m^{-1}$	700.06	*lg*/m	0.3607
pqgh/N	79.488	*khc*/ $N\cdot m^{-1}$	0.151
kqgh/$N\cdot m^{-1}$	0.2425	*phc*/N	13
mzdj/kg	0.0637	*vc*/$m\cdot s^{-1}$	128
t/ms	4.91	*Mz*/	98

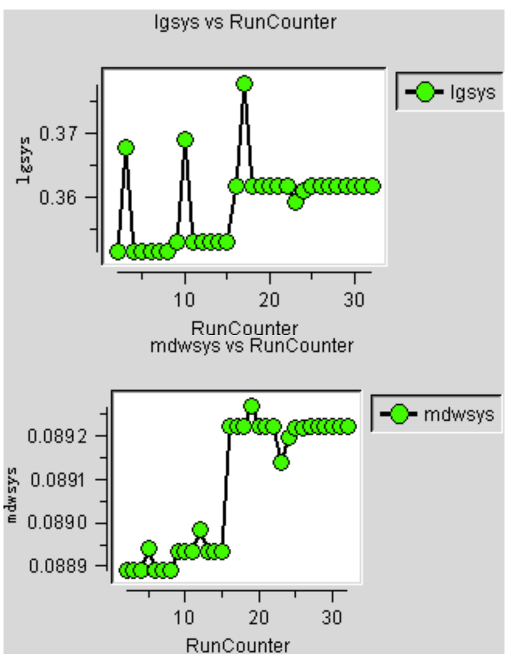

Fig. (1). System-level part parameters iteration process.

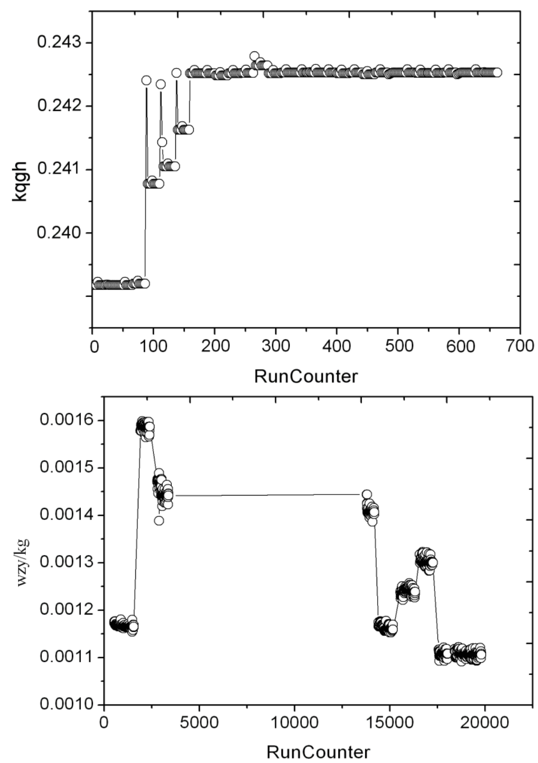

Fig. (2). Subsystem-level optimization part parameters iteration process.

on gradient, with randomly take a plan (may be not a feasible scheme), it regards design parameters basic value as the initial value of the optimization. The optimization process may not be able to jump out the feasible region and causes the failure of optimization process. By adopting the combination of global search and local search method to avoid this possibility, the response surface model only needs to compute the value of the polynomial. It avoids the analyzing of continuous call accurate simulation program and reduces the computational cost. At the same time, the response surface model can improve the robustness of the collaborative optimization method.

Through the multiple disciplines analysis of system and subsystem of, at the termination of the computing, the system level consistency constraints are: *Jndd*=1.88e-12, *Jwdd*=2.327e-15, *Jwuqi*=2e-6, satisfy the constraint conditions *Ji*<0.00001. We get the optimization results as shown in Table **2**. The objective function optimal value of system level iteration 33 times, system level objective function and

Table 3. Compared with key parameter of the design results.

Parameter	Original Design	Single Optimization	Collaborative Optimization
Mz	1	0.981	0.982
P_0	1	0.64	0.85
V_0	1	1.23	1.04
lg	1	0.947	0.904
force	1	0.596	0.598

constraint, design variables iterative process are shown in Fig. (**1**). The optimization iteration process of major parameter is shown in Fig. (**2**).

It uses recoil as the system level target. Each subsystem regards the constraint consistency of main design parameters of the system as the goal and gets up two level four subsystems of collaborative optimization model. From the global viewpoint, it changes previous situation of the optimization confined to a single system and better improves the whole performance of gun system, but not just make one optimal subsystem. Collaborative optimization design results compared with single optimization, the original design are shown in Table **3**, numerical show in proportion.

By comparing, the collaborative optimization design compared with single optimization design, the original design, the barrel length is shortened; In the case of gun pressure reduce, velocity was improved; The collaborative optimization reduces recoil and weight at the same time. Seen from the results, separate optimization by only considering the target optimization results will often get the target value. The optimal value of collaborative optimization in aiming at minimum recoil is larger than single optimization results. This is the result of the collaborative optimization of comprehensive consideration on the whole. By collaborative optimization considering more factors and constraints, the optimization of design parameter values tend to be more original design value. At the same time, it can improve the original design to make it better on the basis of the original design. The result shows that: due to there is no consideration of coupling relationship among various disciplines. Variables subject optimization design problems with coupling variable of complex systems are not suitable for ISFS.

With the combination of global optimization algorithm, simulated annealing algorithm and local optimization algorithm, the collaborative optimization algorithm can solve the multidisciplinary design optimization problem of ISFS and coupled problem.

5. CONCLUSION

This text regards the in ISFS as the research object. Considering the coupling relationship of multiple domain models in the design process, it establishes the design optimization model of ISFS. Based on the full thinking of the coupling relationship between various disciplines, it uses parallel, global optimization algorithm, local optimization search strategy and response surface model to make the multidisciplinary multi-objective optimization design. Through the optimization design, it gains the organic coordination between each field performance and optimized design scheme of the optimal overall system performance.

CONFLICT OF INTEREST

The authors confirm that this article content has no conflict of interest.

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