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Control Allocation for an Over-Actuated Aircraft Based on Within-Visual-Range Air Combat Agility

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ABSTRACT The control allocation problems of an over-actuated aircraft are studied to fully utilize the within-visual-range (WVR) air combat agility. By analyzing the agility requirements of modern WVR air combat, a control effector superiority evaluating method is proposed to identify the control effectors participated in control allocation. An optimized control allocation model is constructed based on the air combat agility. As a case study, the control effector superiority parameters of a typical canard-delta-wing aircraft are evaluated, and the optimized control allocation configuration is built. The combat cycle times of the optimized and other two control allocation configurations are evaluated by pilot-in-the-loop simulation on a ground-based flight simulator. The simulation results show that the optimized control allocation model constructed in this paper can efficiently make use of the agility potentials of the target aircraft, which indicates that the control effector superiority evaluating method and the control allocation model proposed are sound and effective.

INDEX TERMS Air combat agility, control allocation, control effector superiority, over-actuated aircraft.

I. INTRODUCTION

In order to achieve desired performances and reliability, modern fighters are usually equipped with multiple control effectors (MCEs). For example, the closed-coupled canards are used to achieve high angle of attack (AOA) maneuverability; the thrust vectoring is equipped to obtain post-stall maneuverability and controllability; the conventional tails are modified or canceled to improve the stealth; additionally, the innovative control effectors (ICEs), such as split drag rudder (SDR), all moving tips (AMT), and spoiler slot deflectors (SSD), etc., are introduced to improve the controllability of tailless aircraft [1]–[5].

While bringing desired performances to aircraft, MCEs also make the flight control system more complicated. Specifically, the number of control effectors tends to be greater than the number of control parameters, which results in an infinite number of ways to achieve desired control effects. Therefore, aircraft with MCEs is also called over-actuated aircraft [6].

The control system of over-actuated aircraft consists of two parts: a control law, which specifies the total control effect to be produced; and a control allocator, which distributes this control requirement among the individual effectors [7]. Control allocation for over-actuated aircraft has been an active research for over twenty years. According to the previous literature, recent works on control allocation focus on new optimal control allocation algorithms [8], [9], fault tolerant/reconfiguration/adaptive control design based on control allocation [10]–[14], and application of control allocation methods in different kinds of vehicles [15], [16]. However, the effects of control allocation on aircraft performances are rarely considered.

The deflection of control effector not only generates control moments, but also affects the aerodynamic characteristics, especially for ICEs which generate control moments by changing local lifts and drags [5]. The changes in lift and drag will affect the traditional flight performances, including the take-off, climb, cruise, and landing performances, and maneuverability. Compare with conventional aircraft, the control effectiveness of over-actuated aircraft control effector is relatively limited [5], [7]. If control allocation is designed improperly, it will probably cause the effectors to saturate, and hinder the response speed, i.e., agility, accordingly. Besides, ICEs, like SDR and SSD, are usually equipped on high stealth aircraft. Because of their low control effectiveness, the deflection effect on radar cross section (RCS) is not negligible [3]. In summary, control allocation has significant effects on flight and stealth performances.

For aircraft, control performances are important with no doubt, but the most critical is to get desired flight performances that match their aerodynamic design.

Regarding fighters, the most determinant flight performance requirement is getting dominance in air combat [17]. Modern air combat is split into two phases: beyond-visual-range (BVR) and within-visual-range (WVR). For BVR air combat, "first view, first shoot" is the key element, high stealth and supersonic cruise are required accordingly. For WVR air combat, the fighters have to finish the shoot mission by a series of rapid maneuvers in a close range. With the application of allaspect missiles, the critical factor has shifted from achieving a rear aspect firing position to angle superiority, i.e., from maneuverability to agility [18].

To fully utilize the WVR air combat agility potentials by control allocation, this paper aims at transferring the WVR agility requirements into control allocation design criteria and selecting control effectors participated in control based on their aerodynamic characteristics.

The main contributions of this paper are summarized as follows:

1) The control allocation design requirements are determined from the point view of WVR air combat performance.

2) A control effector superiority evaluating method is proposed for determining the control effectors participating in control allocation and the corresponding weighting parameters based on the design requirements.

3) The control allocation model for WVR air combat is built to satisfy the design requirements by selecting a suitable control allocation algorithm.

The remainder of this paper is organized as follows. In Section II, the control allocation problem is formulized. In Section III, the WVR air combat flight performance requirements are transferred into the control allocation design requirements, a control effector superiority evaluating method, and a control allocation model. In Section IV, the effectiveness of the proposed approach is demonstrated by evaluating the combat cycle times (CCTs) of different control allocation configurations.

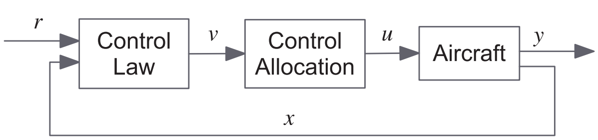

FIGURE 1. The block diagram of an over-actuated aircraft control system.

II. PROBLEM FORMULATION

As shown in Fig. 1, the control system of an over-actuated aircraft consists of two parts: control law and control allocation.

The goal of control allocation is to find a set of permissible control effector deflections to achieve desired control effects. The input is the desired control effect to be produced, i.e., the virtual control input $\boldsymbol{v}(t) \in \boldsymbol{R}^n$. The output is the control effector deflections $\boldsymbol{u}(t) \in \boldsymbol{R}^m$ [6], [14]. For the linear systems,

$$\boldsymbol{B}\boldsymbol{u}(t) = \boldsymbol{v}(\mathrm{t}) \tag{1}$$

where the control effectiveness matrix $\boldsymbol{B}$ is an $n \times m$ matrix with rank n and $n < m$. To incorporate control effector position and rate constraints, it is required that:

$$\boldsymbol{\delta}_{min} \leq \boldsymbol{u}(\mathrm{t}) \leq \boldsymbol{\delta}_{max} \tag{2}$$

$$|\dot{\boldsymbol{u}}(t)| \leq \boldsymbol{\delta}_{rate} \tag{3}$$

where $\boldsymbol{\delta}_{\mathrm{min}}$ and $\boldsymbol{\delta}_{\mathrm{max}}$ are the lower and upper position constraints, and $\boldsymbol{\delta}_{\mathrm{rate}}$ specifies the maximal individual control effector rate.

Since the control allocator is implemented as a part of the time-discrete control system, it is possible to approximate the time derivative as:

$$|\dot{\boldsymbol{u}}(t)| \approx [\boldsymbol{u}(t) - \boldsymbol{u}(t-T)]/T \tag{4}$$

where T is the sample time.

Combining (2)-(4) yields:

$$\underline{\boldsymbol{u}}(t) \leq \boldsymbol{u}(t) \leq \overline{\boldsymbol{u}}(t) \tag{5}$$

$$\begin{cases} \underline{\boldsymbol{u}}(t) = max\{\boldsymbol{\delta}_{\mathrm{min}} - \boldsymbol{u}(t-T) - \boldsymbol{\delta}_{\mathrm{rate}}T\} \\ \overline{\boldsymbol{u}}(t) = max\{\boldsymbol{\delta}_{\mathrm{max}} - \boldsymbol{u}(t-T) + \boldsymbol{\delta}_{\mathrm{rate}}T\} \end{cases} \tag{6}$$

Equation (1) constrained by (5) constitutes the standard formulation of the linear control allocation problem, which can be rewritten as follows:

$$\begin{cases} \boldsymbol{B}\boldsymbol{u}(\mathrm{t}) = \boldsymbol{v}(\mathrm{t}) \\ \underline{\boldsymbol{u}}(t) \leq \boldsymbol{u}(t) \leq \overline{\boldsymbol{u}}(t) \end{cases} \tag{7}$$

There are three possible outcomes for control allocation problems [8]:

1. The over-determined solution ($n < m$). In this case, there are an infinite number of solutions. We can use the extra degrees of freedom to optimize some objectives, such as minimum control deflections, drag, radar signature, etc.

2. The exactly determined solution ($n = m$). In this case, there is one unique control input that produces the desired virtual control input. The task for control allocation is to find this input.

3. The under-determined solution ($n > m$). In this case, the desired virtual control input cannot be produced. We need to use the remaining control effectors to obtain a solution that is as close to the value of v as possible.

This paper focuses on the first case, which is typical in control allocation for over-actuated aircraft.

III. CONTROL ALLOCATION MODEL BASED ON WVR AIR COMBAT AGILITY

A. PERFORMANCE REQUIREMENTS FOR WVR AIR COMBAT

Fighter performance and air combat tactics have been studied since these aircraft was used as military weapons. Each innovation in technology has made a subsequent change in fighter performance evaluation methods and combat tactics. As the all-aspect infrared missiles have become the main WVR air combat weapon, air combat has shifted from a series of sustained maneuvers to short, point-and-shoot maneuvers. Therefore, traditional performance and maneuverability criteria are inadequate to evaluate the aircraft effectiveness in air combat. This has stimulated the development of new performance measures, namely agility metrics [19], [20].

Before the utilization of all-aspect missiles, the demands of achieving stable, rear quarter firing solutions led to extended engagement times and sustained maneuvering. Therefore, the performance measure for air combat effectiveness is maneuverability.

The all-aspect missile has eliminated the need to achieve a rear aspect firing position in an air combat engagement. Pilots only need to aim their weapons at the target. The critical factor for air combat has shifted from achieving a rear aspect firing position to angle superiority and transient maneuvering capabilities, i.e., agility.

B. AGILITY

Agility can be regarded as the time derivative of maneuverability [19]. It requires that the aircraft has the capability to change its flight condition and attitude rapidly as well as maintain high maneuverability.

The agility metrics can be classified into three categories based on the time scale: transient, functional and potential.

1) TRANSIENT AGILITY

Transient agility is concerned with a time scale on the order of 1-5 s, including axial, longitudinal, and lateral.

The most representative axial agility metric is the power onset parameter (POP):

$$\Delta P_s/\Delta t = (P_{sf} - P_{si})/(t_f - t_i) \tag{8}$$

where $P_s = (T - D)V/G$ is the specific excessive power (SEP), T is the engine thrust, D, V and G is the aircraft drag, velocity, and weight, respectively. P_{si} and t_i are the initial SEP and time, P_{sf} and t_f are the final SEP and time. For a given aircraft, lower drag D, i.e., higher lift to drag ratio (L/D) corresponds to larger POP, and higher axial agility.

The most useful longitudinal agility metrics are the maximum positive pitch rate qmax and maximum negative pitch rate qmin, while the most useful lateral agility metric is the time to capture 90° roll angle T_{90}:

$$T_{90} = T_\phi - (\phi_{max} - 90)/\dot{\phi} \tag{9}$$

where T_ϕ is the time to capture the maximum roll angle ϕ_{max}, $\dot{\phi}$ is the roll rate. Higher control effectiveness and control effector actuator rates correspond to larger q_{max}, $|q_{min}|$ and smaller T_{90}, and higher agility accordingly.

2) FUNCTIONAL AGILITY

Functional agility metrics deal with a longer time scale of 10-20 s, including CCT, dynamic speed turn (DST), and pointing margin, etc. Functional metrics usually involve maneuvers made up of a sequence of brief segments of transient agility metrics. Therefore, the determining factors of functional agility are consistent with transient agility.

3) POTENTIAL AGILITY

Potential agility is independent of time [20]. The longitudinal and lateral metrics depend on the control effectiveness to inertias ratio, while the axial metric depends on the thrust to weight ratio. Therefore, higher control effectiveness corresponds to higher potential agility.

4) CONTROL ALLOCATION DESIGN REQUIREMENT OF WVR AIR COMBAT

By synthesizing the transient, functional and potential agility metrics, we observed that high agility depends on high L/D, high control effectiveness, and high control effector actuator rates, which are also the control allocation design requirements.

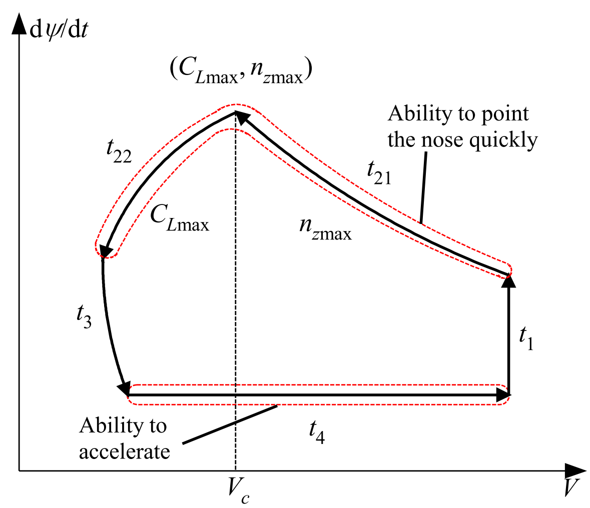

FIGURE 2. Conceptual plot of CCT metric.

5) METRIC FOR VERIFYING WVR COMBAT EFFECTIVENESS

As shown in Fig. 2, CCT is a metric that integrates the requirements of axial, longitudinal, and lateral transient agilities. It is one of the most representative agility metric to quantify WVR combat effectiveness [19].

The time involved with the CCT metric include:

t_1: time to roll 90° and load up to maximum normal load factor;

t_2: time to reach the maximum turn rate and turn 180° degrees;

t_3: time to unload to a 1 g normal load factor and roll out;

t_4: time to accelerate back to the original energy level.

Smaller CCT corresponds to higher WVR combat effectiveness.

C. CONTROL EFFECTOR SUPERIORITY

For over-actuated aircraft, all the control effectors have the capability to control the aircraft, but it does not necessarily mean all of them have to be involved in control for all flight phases. If the control effectors are used improperly, the aerodynamic characteristics and flight performances may not be fully utilized, e.g., the closed-coupled canards are used to generate vortex lift and increase maneuverability by the favorable interference between canard and wing vortices, but their deflection will break this favorable interference and decrease L/D [1]. Besides, from the point view of reliability and complexity of the flight control system, the number of control effectors simultaneously involved in flight control should be as few as possible.

For WVR combat, the most critical performance requirement is agility. The aircraft requires not only high L/D, but also high control effectiveness and high control effector actuator rate. Since the pilot can find the target by eyesight during WVR combat phase, the stealth requirement can be ignored.

Therefore, the control effector superiority of WVR combat can be formulized as:

$$P_{\delta i} = a_K(K_{\delta i} - K_0) + a_m R_{m\delta i} + a_{RL} R_{RL\delta i} \tag{10}$$

where $P_{\delta i}$ is the superiority parameter of the ith control effector, larger $P_{\delta i}$ means higher superiority. $i = 0, 1, \ldots, n-1$, n is the number of control effectors, $i = 0$ corresponds to the reference control effector, which can be any control effector. Different reference effector will change the superiority parameter, but will not affect the proportion and sequence of the effector superiority parameters. a_K, a_m and a_{RL} are the weighting parameters for L/D, control effectiveness and control effector actuator rate limit, respectively. For a given equation, the weighting parameters satisfy that $a_K, a_m, a_{RL} \in [0, 1]$, and their sum equals to 1.

$K_0 = C_{L0}/C_{D0}$ is the aircraft lift to drag ratio with no control effector deflection at a given flight condition, C_{L0} and C_{D0} are the lift and drag coefficient with no control effector deflection. $K_0 = (C_{L0} + \Delta C_{L\delta i})/(C_{D0} + \Delta C_{D\delta i})$ is the aircraft lift to drag ratio with unit deflection of the ith control effector, where $\Delta C_{L\delta i}$, $\Delta C_{D\delta i}$ are the lift and drag coefficient increment per unit deflection of the ith control effector, respectively.

$R_{m\delta i} = C_{m\delta i}/C_{m\delta 0}$ is the ratio between the control effectiveness of the ith and the reference control effector.

$R_{L\delta i} = R_{L\delta i}/R_{L\delta 0}$ is the ratio between the control effector rate limit of the ith and the reference control effector.

For WVR combat, larger L/D increment, control effectiveness per unit deflection of the control effector, and higher actuator rate will lead to larger $P_{\delta i}$ and higher superiority.

The control effector superiority parameters can be used to determine the control effectors participated in control allocation, as well as the control effectors weighting parameters in control allocation.

D. CONTROL ALLOCATION MODEL

After determining the performance requirements and control effectors superiority, a proper allocation algorithm should be chosen to build the control allocation model.

In recent years, several types of control allocation algorithms have been proposed, including generalized inverse, daisy chaining, direct allocation, linear/quadratic programming, and dynamic allocation, etc. [7]–[9]. We choose dynamic control allocation using constraint quadratic programming as the allocation algorithm for WVR combat phase, because of its capability of providing rapid response and considering different actuator bandwidth [21], which coincides with the WVR agility requirement.

The dynamic control allocation algorithm can be considered as a sequential quadratic programming (SQP) problem [8], [21]:

$$\begin{aligned} \boldsymbol{u}(t) &= \arg\min_{u(t)\in\Omega} \left\{ \left\| \boldsymbol{W}_1[\boldsymbol{u}(t) - \boldsymbol{u}_s(t)] \right\|^2 \right. \\ &\qquad \left. + \left\| \boldsymbol{W}_2[\boldsymbol{u}(t) - \boldsymbol{u}(t-T)] \right\|^2 \right\} \\ \Omega &= \arg\min_{u(t)\in\Omega} \left\| \boldsymbol{W}_v[\boldsymbol{B}\boldsymbol{u}(t) = \boldsymbol{v}(t)] \right\| \end{aligned} \tag{11}$$

where $\boldsymbol{u}(t), \boldsymbol{u}(t-T) \in \boldsymbol{R}^m$ are the true control inputs of the present and last time step, $\boldsymbol{u}_s(t) \in \boldsymbol{R}^m$ is the desired steady-state control input, $\boldsymbol{v}_s(t) \in \boldsymbol{R}^n$ is the virtual control input. $\boldsymbol{B} \in \boldsymbol{R}^{n\times m}$ is the control effectiveness matrix. $\boldsymbol{W}_1$, $\boldsymbol{W}_2$, and $\boldsymbol{W}_v$ are the weighting matrices of proper dimensions. $\|\cdot\|$ denotes the l_2-norm defined by $\|\boldsymbol{u}\| = (\boldsymbol{u}^T\boldsymbol{u})^{1/2}$.

The desired steady-state solution u_s can be determined by generalized inverse:

$$\min \|\boldsymbol{u}_2\|_2, \quad s.t. \quad \boldsymbol{B}\boldsymbol{u}_s = \boldsymbol{v} \tag{12}$$

If no actuators are saturated in the solution to (11), the actuator constraints can be disregarded, and the optimization problem reduces to:

$$\begin{aligned} &\min_{u(t)} \left\| \boldsymbol{W}_1[\boldsymbol{u}(t) - \boldsymbol{u}_s(t)] \right\|^2 + \left\| \boldsymbol{W}_2[\boldsymbol{u}(t) - \boldsymbol{u}(t-T)] \right\|^2 \\ &s.t. \quad \boldsymbol{B}\boldsymbol{u}(t) = \boldsymbol{v}(t) \end{aligned} \tag{13}$$

Assume that the weighting matrices $\boldsymbol{W}_1$ and $\boldsymbol{W}_2$ are symmetric and $\boldsymbol{W} = (\boldsymbol{W}_1^2 + \boldsymbol{W}_2^2)^{1/2}$ is nonsingular, which can be determined by generalized inverse. According to the derivative process in [8], the control allocation problem has the solution:

$$\boldsymbol{u}(t) = \boldsymbol{E}\boldsymbol{u}_s(t) + \boldsymbol{F}\boldsymbol{u}(t-T) + \boldsymbol{G}\boldsymbol{v}(t) \tag{14}$$

where

$$\begin{aligned} \boldsymbol{E} &= (\boldsymbol{I} - \boldsymbol{G}\boldsymbol{B})\boldsymbol{W}^{-2}\boldsymbol{W}_1^2 \\ \boldsymbol{F} &= (\boldsymbol{I} - \boldsymbol{G}\boldsymbol{B})\boldsymbol{W}^{-2}\boldsymbol{W}_2^2 \\ \boldsymbol{G} &= \boldsymbol{W}^{-1}(\boldsymbol{B}\boldsymbol{W}^{-1})^{+} \end{aligned} \tag{15}$$

We observed that the transient solutions of control effectors $\boldsymbol{u}(t) = \boldsymbol{E}\boldsymbol{u}_s(t) + \boldsymbol{F}\boldsymbol{u}(t-T) + \boldsymbol{G}\boldsymbol{v}(t)$ depend on $\boldsymbol{W}$, i.e., the weighting matrices $\boldsymbol{W}_1$ and $\boldsymbol{W}_2$.

A large diagonal entry in $\boldsymbol{W}_1$ will make the corresponding control effector converge quickly to its desired position; therefore, the parameters of $\boldsymbol{W}_1$ can be selected based on the control effector superiority, higher superiority corresponds to larger matrix element. And a large $\boldsymbol{W}_2$ entry will prevent the control effector from moving too fast, i.e., minimize the change in the control input compared to the preceding sampling instant.

IV. SIMULATION RESULTS

We take the ADMIRE (Aero-Data Model in Research Environment) developed by Swedish Defense Research Agency (FOI) [22], as an example. Control allocation for WVR combat will be implemented and evaluated on the basis of control allocation model built in this paper.

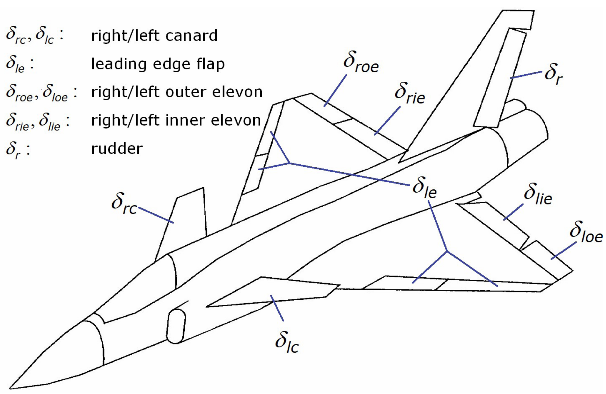

FIGURE 3. Layout of the example aircraft.

As shown in Fig. 3, the aerodynamic control surfaces of ADMIRE include two close-coupled canards, four elevons, a leading-edge flap (LEF) and a rudder. The maximal allowed deflections and angular rate of the control surfaces are given in Table 1.

TABLE 1. Control surface deflection limits.

Control Surface	Min	Max	Angular Rate
Rudder	$-30°$	$30°$	$\pm 30°/s$
Eleven	$-55°$	$25°$	$\pm 50°/s$
Leading Edge Flap	$0°$	$30°$	$\pm 20°/s$

The deflection limits, angular rates and aerodynamic characteristics are equal for δ_{rc} and δ_{lc}, δ_{roe} and δ_{loe}, δ_{rie} and δ_{lie}, respectively. Therefore, we can consider these control surfaces as one canard, one outer elevon and one inner elevon:

$$\delta_c = (\delta_{rc} + \delta_{lc})/2$$
$$\delta_{ei} = (\delta_{rie} + \delta_{lie})/2$$
$$\delta_{ey} = (\delta_{roe} + \delta_{loe})/2 \tag{16}$$

for evaluating the control surface superiority.

A. CONTROL EFFECTOR SUPERIORITY

For WVR combat, the critical performance requirement is agility, which depends on the L/D, control effectiveness, and control effector actuation rate. The effects of L/D, control effectiveness, and control effector actuation rate on WVR combat effectiveness are approximately equivalent, and the effect of effector actuation rate is slightly lower than the first two parameters. Therefore, the weighting parameters a_K, a_m and a_{RL} can be selected as 0.35, 0.35 and 0.3, respectively. By choosing the inner elevon δ_{ei} as the reference control effector, the superiority parameters at typical WVR combat condition ($H = 5000\ m, M = 0.8$) are given in Fig. 4. From the highest superiority to the lowest one, the control effector sequence for WVR combat is inner elevon, outer elevon, and canard.

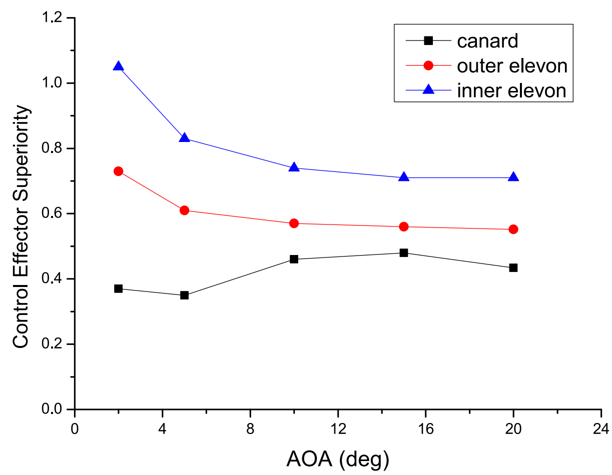

FIGURE 4. Superiority parameters of longitudinal control effector.

TABLE 2. Effects on L/D of leading edge flap.

AOA(deg)	$(L/D)_0$	δ_{le}(deg)	$(L/D)_{\delta le}$
α_{trim}	7.13	0	7.13
5	10.45	10	10.52
10	6.23	30	6.87
15	4.09	30	4.53
20	3.05	30	3.83

The function of closed-coupled canard is to increase the lift coefficient at high AOA by the favorable interference between canard and wing vortices. Once this favorable interference is broken, the L/D will decrease significantly [1]. Furthermore, the control effectiveness is relatively low because of the short moment arm. Hence, for most flight phases, it is preferred to hold the close-coupled canard at a certain deflection to get high L/D. However, during the initial phase of a pitch maneuver, there is an unwanted non-minimum phase tendency of the load factor [23], which can be counteracted by utilizing the canards at high frequency [8]. As shown in Table 2 and Fig. 5, the LEF deflection can increase L/D significantly at high AOA, while it has almost

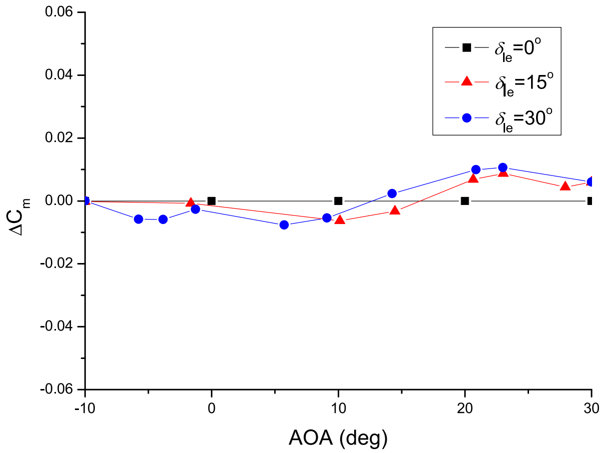

FIGURE 5. Pitching moment coefficient generated by LEF deflection.

no effect on pitching moment. Besides, LEF deflection can improve the flow separations and the lateral-directional stability at high AOA.

Therefore, LEF can deflect downwards directly at high AOA during WVR air combat phase.

B. CONTROL ALLOCATION SCHEME

The control allocation for WVR combat can be formulized as:

$$\begin{aligned}&\min_{u(t)} \left\| W_1[u(t) - u_s(t)] \right\|^2 + \left\| W_2[u(t) - u(t-T)] \right\|^2 \\ &s.t.\ \ Bu(t) = v(t) \\ &\qquad \underline{u} \le u(t) \le \overline{u}\end{aligned}$$

where

$$u = [\delta_{lc} \quad \delta_{rc} \quad \delta_{loe} \quad \delta_{lie} \quad \delta_{rie} \quad \delta_{roe} \quad \delta_r]^T \tag{17}$$

Steady-state solution us can be determined by generalized inverse:

$$\min_{u_s} \|u_s\|^2, \quad Bu_s = v, \quad u_{s,1} = u_{s,2} = 0 \tag{18}$$

where $u_{s,1}$ and $u_{s,2}$ are steady-state solution of the canards. $u_{s,1} = u_{s,2} = 0$ means that the canards only deflect at high frequency range. Therefore, the non-minimum phase tendency of the load factor can be countered, as well as the vortex lift will be kept.

Since a large diagonal entry in W_1 will make the corresponding actuator converge quickly to its desired position, deflecting control effectors with high control effectiveness rapidly can satisfy the agility requirements. For the target aircraft, the control effector superiority parameters for WVR combat is $P_{\delta ei} > P_{\delta eo} > P_{\delta c}$, thus the elements of W_1 can be selected as:

$$W_1 = \text{diag}([1, 1, 2, 3, 3, 2, 2]) \tag{19}$$

Similarly, since a large W_2 entry will prevent the actuator from moving too fast, the parameters of W_2 can be selected based on the rate limit of control effectors. For the target aircraft, the rates of control effectors participated in control allocation are all $50°/s$, thus:

$$W_2 = \text{diag}([5, 5, 5, 5, 5, 5, 5]) \tag{20}$$

C. EVALUATION RESULTS

We evaluate the CCT of ADMIRE with the same FCL and three different control allocation configurations:

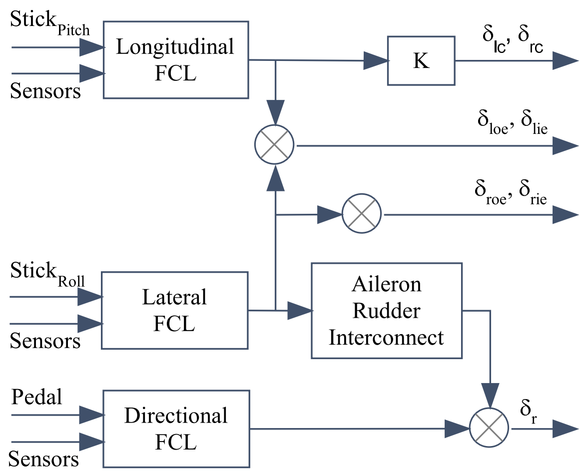

FIGURE 6. Schematic of ganged control allocation.

1) Ganged, divide the controls into different groups which corresponded to different moment commands. As shown in Fig. 6, for pitch control, collective canards and elevons are used; for roll control, differential elevons are used.

2) Dynamic Allocation (DA), as shown in Fig. 7, LEF does not deflect, and canards only participate in control at high frequency.

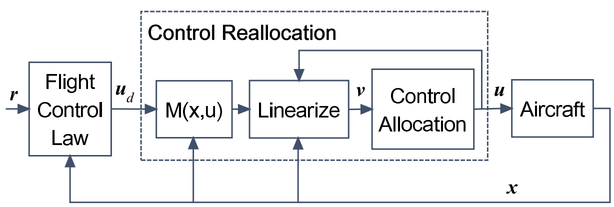

FIGURE 7. Schematic of dynamic allocation.

3) Dynamic Allocation with leading-edge flap (DA with LEF), canards only participate in control at high frequency, and LEF deflects with the AOA.

The simulation results of the considered three control allocation configurations, which are completed by pilots on a ground-based flight simulator, are given in Fig. 8 to Fig. 10. Flight conditions for simulation are all typical WVR combat flight condition, where $H = 5000\ m$, $Ma = 0.8$.

Fig. 8 gives the CCT plots of three different control allocation configurations. Since the differences between

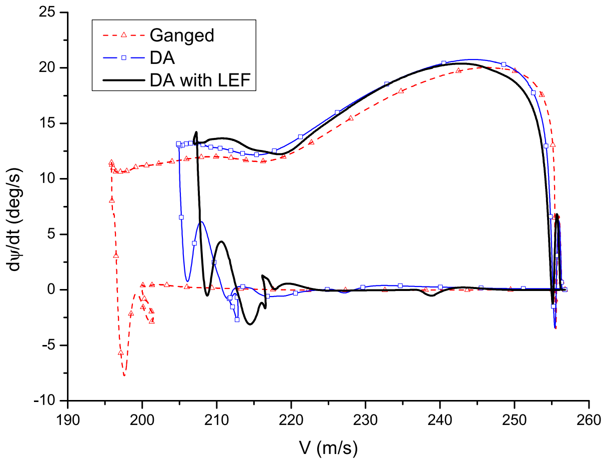

FIGURE 8. **Combat cycle time plot of three configurations.**

"DA" and "DA with LEF" lies in whether the LEF is used, and the deflection of LEF will decrease drag coefficient and barely effect lift coefficient, so the turn rate of "DA" and "DA with LEF" are nearly equivalent and speed loss of "DA with LEF" is smaller than "DA." For "Ganged" configuration, canards are participated in control all the time, the favorable interference between canard and wing vortices is broken and the high AOA aerodynamic performance of the aircraft cannot be fully utilized. Therefore, the turn rate of "Ganged" configuration is slightly smaller than the other two configurations, while the speed loss is apparently larger than the other two configurations.

Fig. 9 gives the lift and drag coefficient plots of three different control allocation configurations during CCT. The maximum lift coefficients of "DA" and "DA with LEF" are nearly equivalent, while the maximum lift coefficient of "Ganged" is smaller than the other two. The drag coefficient of "Ganged" is the largest, the drag coefficient of "DA" is smaller, and the drag coefficient of "DA with LE" is much smaller than the other two. Higher lift coefficient makes a higher turn rate while lower drag coefficient makes a smaller speed loss. This coincides with the results in Fig. 8.

As shown in Fig. 10, the canard deflections of "DA" and "DA with LEF" are much smaller than that of "Ganged." Since canards participate in control, the elevons deflection of Ganged is smaller than that of "DA" and "DA with LEF." For "DA with LEF" configuration, the LEF deflects with the AOA.

TABLE 3. **Combat cycle time of 3 configurations.**

Control Allocation Configuration	$t_1+t_2+t_3$ (s)	t_4 (s)	total CCT (s)
Ganged	15.53	12.35	27.88
DA	13.34	10.57	23.91
DA with LEF	13.27	10.40	23.67

The CCTs of the three control allocation configurations are shown in Table 3. Since t_1 and t_3 are much smaller compared to t_2 and t_4, t_1 and t_3 will be merged into t_2, and considered as the time to turn 180°. As shown in Table 3, configuration "DA with LEF" has the shortest CCT, "DA" takes the second place, and "Ganged" has the longest CCT.

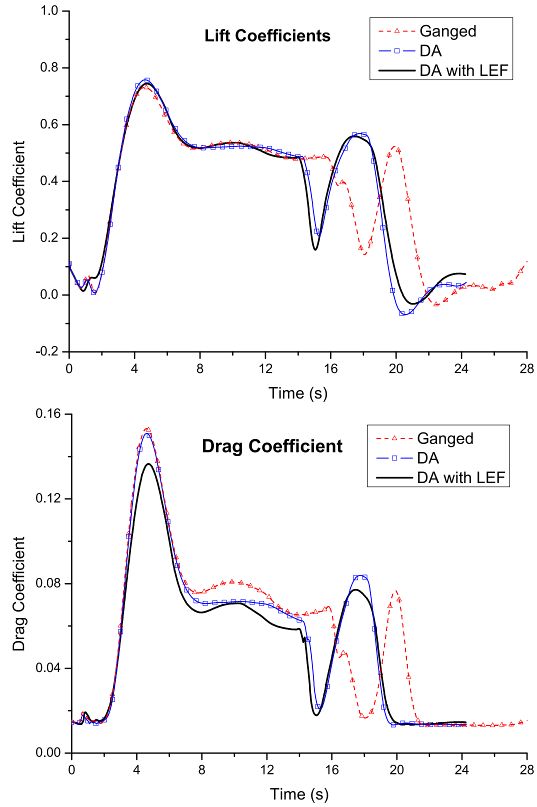

FIGURE 9. **Lift and drag coefficient of three configurations during CCT.**

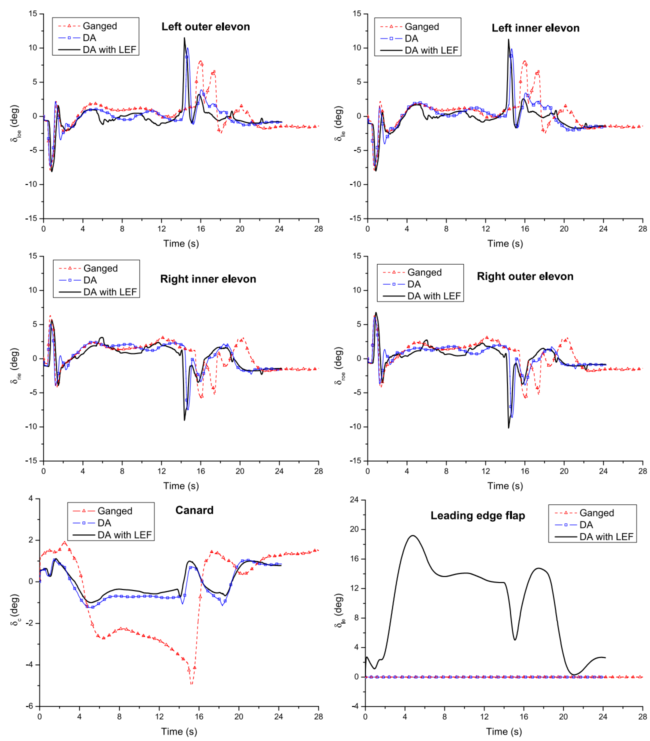

FIGURE 10. **Time history of control surface deflection of three configurations during CCT.**

The evaluating results show that, the control allocation model proposed in this paper can make full use of the agility potential, which indicates that the proposed model is sound.

V. CONCLUSIONS

In this paper, the relations between control allocation and agility are analyzed. Based on the requirements of agility, a control effector superiority evaluation method is proposed, and further an optimized control allocation model based on dynamic control allocation algorithm is formulized.

(1) Control effectors superiority evaluating method proposed in this paper can be used in identifying the control effectors participated in control. It can simplify the control allocation design as well as ensure the performance requirements.

(2) The simulation results show that the control allocation model formulized in this paper can efficiently make use of the agility potentials of the target aircraft.

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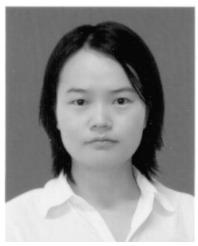

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