AN EVALUATION MODEL FOR CONTROL EFFECTOR SUPERIORITY BASED ON PERFORMANCE REQUIREMENTS

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Abstract

To simplify the control allocation design, a quantitative evaluation model for over-actuated aircrafts is proposed based on performance requirements. The flight requirements of different flight phases, including beyond visual range (BVR), within visual range (WVR), takeoff and landing, are analyzed. Quantitative evaluation models of control effector superiority of different flight phases are proposed. Control effector superiority parameters and flight performance indices of a typical over-actuated aircraft are evaluated. The simulation results show that the flight performance results coincide with the control effector superiority results, which indicates the control effector evaluation model is reasonable and effective.

1 General Introduction

To achieve desired performances, modern fighters are usually equipped with multiple control effectors (MCE). For example, closed-coupled canards are used to obtain high angle of attack (AOA) maneuverability; thrust vectoring are equipped to obtain post stall maneuverability and controllability; tails are modified or canceled to improve the stealth; additionally, innovative control effectors such as all moving tips (AMT), spoiler slot deflectors (SSD), split drag rudder (SDR) are introduced to improve the controllability of tailless aircrafts [1-4].

Although MCEs bring desired performances to the aircraft, they also make the flight control 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, aircrafts with MCEs are also called over-actuated aircrafts.

An effective method is necessary to solve the control allocation problem for over-actuated aircrafts. Their control system usually 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 separate actuators [5].

The control allocation will affect the aircraft performance measures significantly. The deflection of control effector will generate control moments as well as change the lift and drag, i.e. affect the traditional performance measures. MCEs also mean that the control effectiveness of a single control effector is relatively limited. If control allocation is designed inappropriately, it will probably cause the actuators to saturate and hinder the agility [6]. Besides, innovative control effectors, like AMT and SSD, are usually equipped on high stealth tailless aircrafts, the deflection effect on Radar cross section (RCS) are not negligible for high stealth aircrafts.

For over-actuated aircrafts, all the control effectors have the ability to control the aircraft. In other words, they all have a certain influence on the performances when activated. However, it does not necessarily mean they have to be involved in control for all flight phases. If the control effectors are used inappropriately, the performances will not be fully utilized [5.6]. Besides, from the angle 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. If we can identify the control effectors participate in control allocation before the control allocation design, we can fully utilize the performance potentials, ensure the performance requirements as well as simplify the control allocation design.

According to the previous literatures, only daisy chaining control allocation has considered the control effectors' superiority problem [5, 7]. The method of daisy chaining usually divides the controls into groups, with each successive grouping being used only when the previous groupings fail to achieve the desired moment. However, its ability to provide admissible and optimized solutions for physically attainable moments is very limited [8]. Besides, there is no detailed standard to divide these controls.

This paper focuses on how to evaluate the superiority of the control effectors and identify the controls participated in control allocation.

2 Control Effector Superiority Standards

2.1 General Performance Requirements

Different flight phases have different performance requirements. Accordingly, the control effector superiority evaluating standards are different.

For fighters, the most critical performance requirement is getting dominance in air combat. As the development of weapons and detecting systems, modern air combat can be divided into BVR combat and WVR combat.

"First view, first shot, first kill" is the key element of BVR combat. To shoot the BVR missiles, the fighters have to cruise at supersonic speed. To get increased viability and combat effectiveness, high stealth is needed. Therefore, the critical performance requirements of BVR combat are high stealth and supersonic cruise. [9]

For WVR combat, the fighters have to finish the shoot mission by a series of rapid maneuvers. Therefore, the most critical performance requirements are maneuverability and agility [10]. The aircraft requires not only high lift to drag ratio, but also the ability to change its flight condition and attitude rapidly, which needs high control effectiveness and actuator response rate. Since the pilot can find the target by eyesight during WVR combat phase, the stealthy performance can be ignored.

Besides, for modern fighters, short field performances are needed for base survival.

2.2 BVR phase

During BVR combat phase, the aircraft requires high cruise and stealth performances. Therefore, control effectors which are favorable for L/D and stealthy performance have higher superiority.

Stealth performance is usually measured by Radar Cross Section (RCS).

Cruise Performance depends on the lift to drag ratio, e.g. the drag. The drag of aircraft consists of zero-lift drag, induced drag and drag increment caused by control effector deflection. For high subsonic and supersonic speeds, the zero-lift drag term will also include the wave drag. Zero-lift drag is independent of control effector deflection. Induced drag lies on the trim AOA, smaller trim AOA corresponds to smaller induced drag. Drag increment lies on the control effectiveness and control effector deflection's effect on lift to drag ratio, higher control effectiveness corresponds to smaller control effector deflection and smaller drag increment.

To reduce the trim AOA, the trimmed lift curve slope should be increased.

$$\begin{aligned} P_{\delta i} &= a_{LD}\left((L/D)_{\delta i} - (L/D)_0\right) + a_m R_{m\delta i} \\ &\quad + a_{L\alpha} C_{m\alpha}\,\mathrm{sgn}(L_\delta) - a_{RCS} R_{RCS\delta i} \end{aligned} \tag{1}$$

Where L_δ is the arm between the center of gravity (CG) and the aerodynamic center of the control effector; $(\bar{x}_G - \bar{x}_F)$ is static margin. For longitudinal static stable aircraft, control effector with $L_\delta < 0$ is favorable for trim; and for unstable aircraft, control effector with $L_\delta > 0$ is favorable for trim.

Therefore, the evaluation standard for control effector superiority for BVR combat phase can be expressed mathematically as

$$\begin{aligned} P_{\delta i} &= a_{LD}\left((L/D)_{\delta i} - (L/D)_0\right) + a_m R_{m\delta i} \\ &\quad + a_{L\alpha} C_{m\alpha}\,\mathrm{sgn}(L_\delta) - a_{RCS} R_{RCS\delta i} \end{aligned} \tag{2}$$

Where $P_{\delta i}$ is the superiority parameter of the *i-th* control effector. Larger $P_{\delta i}$ means higher superiority. $i = 0,1,\cdots n-1$, control effector with $i = 0$ is the reference control effector.

$$(L/D)_0 = \frac{C_{L0}}{C_{D0}} \tag{3}$$

$$(L/D)_{\delta i} = \frac{C_{L0} + \Delta C_{L\delta i}}{C_{D0} + \Delta C_{D\delta i}} \tag{4}$$

$$R_{m\delta i} = \left| \frac{\Delta C_{m\delta\iota}}{\Delta C_{m\delta 0}} \right| \tag{5}$$

$$R_{RCS\delta i} = \frac{\Delta RCS_{\delta i}}{RCS_0} \tag{6}$$

$(L/D)_0$, C_{L0} and C_{D0} are the lift to drag ratio, lift coefficient and drag coefficient for clean configuration (no control effector deflection) at a given flight condition. $\Delta C_{L\delta i}$, $\Delta C_{D\delta i}$ and $\Delta C_{m\delta\iota}$ are the lift, drag and pitching moment coefficient increment per unit deflection of the *i-th* control effector.

$\mathrm{sgn}(L_\delta)$ is the sign of the lift arm, according to the sign convention, L_δ is positive for controls aft of CG.

$R_{RCS\delta i}$ is the ratio of RCS increment per unit deflection to RCS of clean configuration.

$a_{LD}, a_m, a_{L\delta}$ and a_{RCS} are the weighting parameters for the L/D, control effectiveness, lift curve slope and stealth respectively. The weighting parameter satisfy that $a_{LD}, a_m, a_{L\delta}$ $a_{RCS} \in [0,1]$, and their sum equals to 1. The weighting parameters depend on the performance requirements, aerodynamic characteristics of the aircraft and control effectors, and actuator performance. Higher weighting responds to higher requirements.

2.3 WVR phase

During WVR combat phase, the aircraft requires not only high lift to drag ratio, but also the ability to change its flight condition and attitude rapidly, which needs high control effectiveness and actuator response rate. Since the pilot can find the target by eyesight, the stealth performance can be ignored during WVR combat phase. Therefore, the superiority of control effectors can be formalized as

$$P_{\delta i} = a_{LD}\left[(L/D)_{\delta i} - (L/D)_0\right] + a_m R_{m\delta i} + a_{rl} R_{rl\delta i} \tag{7}$$

$$R_{rl\delta i} = \frac{RL_{\delta i}}{RL_{\delta 0}}$$

$R_{rl\delta i}$ is the actuator rate ratio of the *i-th* and the reference control effector.

a_{LD}, a_m and a_{rl} are the weighting parameters for L/D, control effectiveness and rate limit characteristics respectively. The weighting parameters depend on the performance requirements, aerodynamic characteristics of the aircraft and control effector, and the actuator performance.

For a given equation, the weighting parameters satisfy that $a_{LD}, a_m, a_{rl} \in [0,1]$, and their sum equals to 1. For WVR combat, larger L/D increment, higher control effectiveness and higher actuator rate leads to larger $P_{\delta i}$ and higher superiority accordingly.

2.4 Takeoff and landing

Generally, takeoff and landing do not require stealth. However, due to the low dynamic pressure, the control effectiveness is relatively low, and the actuator positions and rates of the control effectors are easy to saturate. Therefore, high actuator performances are needed.

To get short ground roll distance, high lift and noseup pitching moment are needed for takeoff and landing before touchdown (TD), while low lift and high drag are required for landing after TD.

Therefore, for takeoff and landing before TD, the superiority of control effectors can be formalized as

$$P_{\delta i} = a_L R_{L\delta i} + a_m R_{m\delta i} + a_{rl} R_{rl\delta i} \tag{8}$$

For landing after TD, the superiority of control effectors can be given by

$$P_{\delta i} = -a_L R_{L\delta i} + a_D R_{D\delta i} \tag{9}$$

Since nose-up pitching moment is needed for takeoff and landing, the control effectiveness term is different with free-flight condition

$$R_{m\delta i} = \frac{\Delta C_{m\delta i}}{|\Delta C_{m\delta 0}|} \tag{10}$$

$$R_{L\delta i} = \frac{\Delta C_{L\delta i}}{|\Delta C_{L\delta 0}|} \tag{11}$$

$$R_{D\delta i} = \frac{\Delta C_{D\delta i}}{|\Delta C_{D\delta 0}|} \tag{12}$$

a_L, a_m, a_{rl}, a_D are the weighting parameters of the lift, pitching up control effectiveness, rate limit and drag characteristics respectively. For a given equation, the weighting parameters satisfy that a_L, a_m, a_{rl}, $a_D \in [0,1]$, and their sum equals to 1.

3 Simulation Results

We take the ADMIRE (Aero-Data Model in Research Environment) developed by FOI [11], as example, to evaluate and validate the control effector superiority.

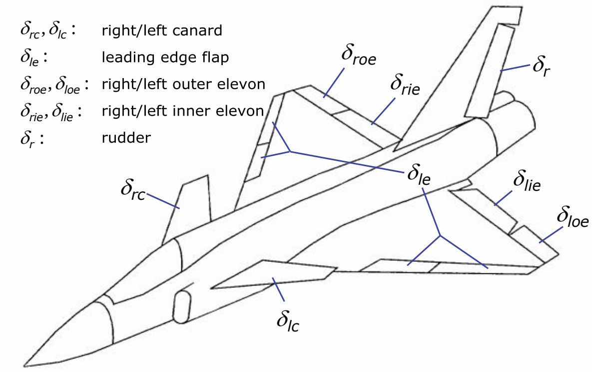

Fig. 1 Layout of the example aircraft

As shown in Fig.1, the control surfaces of ADMIRE include two close-coupled canards, four elevons, a leading-edge flap (LEF), a rudder and horizontal/vertical thrust vectoring (TV). The deflection and angular rate limits are given in Table 1.

Table 1 Control surface deflection limits

Control surface	Min	Max	Angular rate
Canard	-55°	25°	±50°/s
Rudder	-30°	30°	±50°/s
Elevon	-25°	25°	±50°/s
LEF	0°	30°	±20°/s
TV	-25°	25°	±25°/s

Since the deflection limits, angular rate and aerodynamic characteristics are equal for δ_{rc} and δ_{lc}, δ_{roe} and δ_{loe}, δ_{rie} and δ_{lie} respectively, these control surfaces can be considered as one canard, one outer elevon and one inner elevon in evaluating the control effector superiority.

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

3.1 BVR phase

3.1.1 Superiority Evaluation

Using thrust vectoring (TV) during BVR phase will bring significant thrust loss. Besides, for the example aircraft, LEF deflection will reduce the lift instead of reduce the drag at small AOA. Therefore, the control effectors participate in control at BVR phase include canard δ_c, inner elevon δ_{ei} and outer elevon δ_{eo}.

Inner elevon is taken as the reference control effector. Since the ADMIRE is not a stealth aircraft, the weighting parameters a_{AD}, $a_{L\delta}$, a_{RCS} can be selected as 0.8, 0.2 and 0.

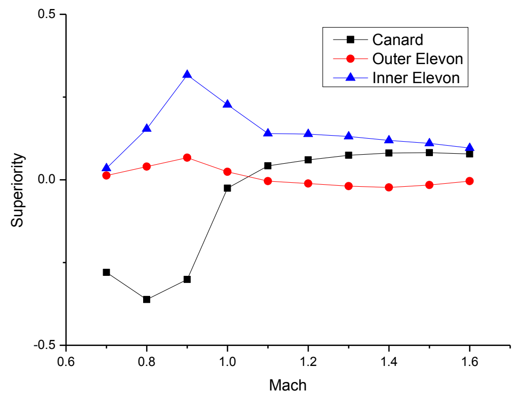

Fig. 2 Superiority parameters of BVR phase

The superiority parameters of these 3 control effectors are shown in Table 2 and Fig.4.

When $M \le 1$, inner elevon has the highest superiority, while canard has the lowest. This is because ADMIRE uses closed-coupled canards, whose main function is using the beneficial interference of vortices to increase $C_{L\max}$ and α_{stall}. At small and medium AOA, the drag increment generated by canard deflection is higher that lift increment.

When $M > 1$, inner elevon has the highest superiority, while outer elevon has the lowest. This is because at supersonic condition, the control effectiveness of outer elevon reduces rapidly.

3.1.2 Simulation Verification

The trimmed L/D, i.e. the cruise performence by using different control effector are shown in Figure 2. When $M \le 1$, inner elevon has the highest L/D, while canard has the lowest.

When $M > 1$, inner elevon has the highest L/D, while outer elevon has the lowest. The performance results coincide with the superiority results, which means the superiority model of BVR phase is reasonable.

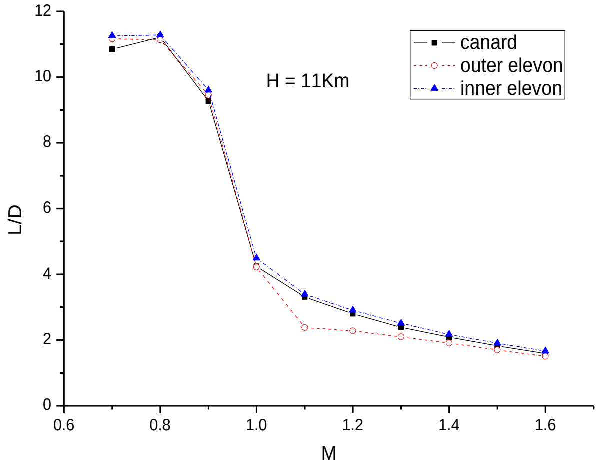

Fig. 3 Trimmed L/D of different control effectors

3.2 WVR Phase

3.2.1 Superiority Evaluation

WVR combat requires high maneuverability and agility. Maneuverability depends on the lift drag ratio L/D, while transient agility depends on the control effectiveness and actuator rate. Functional agility is affected by all the three factors. The effects of L/D, control effectiveness and actuator rate on WVR combat effectiveness are approximately equivalent, and the effect of actuator is slightly lower than the first two parameters.

Since $a_{LD}, a_m, a_{rl} \in [0,1]$, and their sum equals to 1, the weighting parameters a_{LD}, a_m, a_{rl} can be selected as 0.35, 0.35 and 0.3.

Table 2 Superiority parameters of BVR phase

Ma	$C_{m\alpha}$ (1/rad)	$(L/D)_0$	$(L/D)_\delta$			$R_{m\delta i}$			$P_{\delta i}$		
			δ_c	δ_{eo}	δ_{ei}	δ_c	δ_{eo}	δ_{ei}	δ_c	δ_{eo}	δ_{ei}
0.7	0.132	10.76	10.24	10.72	10.76	0.59	0.62	1	-0.280	0.013	0.035
0.8	0.103	10.95	10.26	10.98	11.11	0.55	0.63	1	-0.362	0.040	0.154
0.9	0.063	9.78	9.17	9.94	10.17	0.46	0.58	1	-0.301	0.067	0.317
1.0	-0.246	4.87	4.71	5.05	5.22	0.52	0.55	1	-0.025	0.024	0.227
1.1	-0.418	3.63	3.53	3.78	3.91	0.71	0.51	1	0.042	-0.004	0.140
1.2	-0.418	3.05	2.98	3.17	3.32	0.69	0.47	1	0.060	-0.011	0.138
1.3	-0.413	2.60	2.57	2.72	2.86	0.66	0.45	1	0.074	-0.019	0.131
1.4	-0.407	2.23	2.23	2.34	2.48	0.67	0.44	1	0.081	-0.023	0.119
1.5	-0.378	1.93	1.95	2.04	2.17	0.70	0.43	1	0.082	-0.016	0.110
1.6	-0.344	1.69	1.72	1.79	1.90	0.89	0.41	1	0.078	-0.004	0.096

Table 3 Superiority parameters of WVR phase

AOA (deg)	$(L/D)_0$	$(L/D)_\delta$			$R_{m\delta i}$			$P_{\delta i}$		
		δ_c	δ_{eo}	δ_{ei}	δ_c	δ_{eo}	δ_{ei}	δ_c	δ_{eo}	δ_{ei}
trim	7.13	6.65	7.74	8.31	0.54	0.62	1	0.37	0.73	1.05
5	10.45	9.91	10.66	10.89	0.53	0.62	1	0.35	0.61	0.83
10	6.23	6.10	6.30	6.37	0.45	0.62	1	0.46	0.57	0.74
15	4.09	4.05	4.12	4.14	0.49	0.63	1	0.48	0.56	0.71
20	3.05	3.03	3.06	3.07	0.35	0.63	1	0.434	0.552	0.71

Table 4 Influence on L/D of LEP

AOA(deg)	C_{L0}	C_{D0}	$(C/D)_0$	δ_{le} (deg)	$\Delta C_{L\delta le}$	$\Delta C_{D\delta le}$	$(C/D)_{\delta le}$
trim	0.082	0.0115	7.13	0	0	0	7.13
5	0.2907	0.0278	10.45	10	-0.003	-0.002	10.52
10	0.5884	0.0943	6.23	30	-0.017	-0.009	6.87
15	0.8861	0.2164	4.09	30	-0.022	0.021	4.53
20	1.1838	0.3381	3.5	30	-0.0456	-0.0289	3.83

The superiority parameters of δ_c, δ_{ei} and δ_{eo} are shown in Table 3.

From the highest superiority to the lowest, the control effector sequence for WVR phase is inner elevon, outer elevon and canard. The superiority parameter of elevon decrease as AOA increase, while canard has opposite tendency. This is because elevon locates at the trailing edge of the wing, the wing flow separation has strong effect on the elevon effectiveness, while canard is not affected by the wing flow separation.

As indicated in Table 4, at high AOA, the LE deflection will increase the L/D effectively.

3.2.2 Simulation Verification

Since one single control surface cannot satisfy the control requirements of WVR phase, the verification will be accomplished by comparing the combat cycle time (CCT) of different control surface sets with same FCL and control allocation, as shown in Fig. 4 and Table 5.

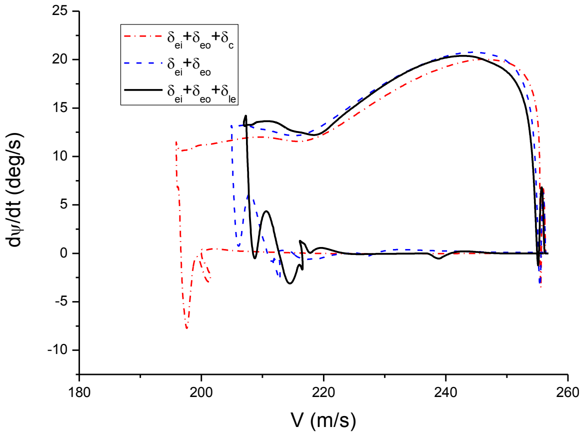

Fig. 4 CCT plot of different control surface sets

The time involved with the CCT metric include:

t_1: time to roll 90 degrees 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 1g normal load factor and roll out;

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

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 °.

Table 5 CCT of different control surface sets

Control surface sets	$t_1+t_2+t_3$ (s)	t_4 (s)	CCT (s)
$\delta_{ei}+\delta_{eo}+\delta_c$	15.53	12.35	27.88
$\delta_{ei}+\delta_{eo}$	13.34	10.57	23.91
$\delta_{ei}+\delta_{eo}+\delta_{le}$	13.27	10.40	23.67

As shown in Table 5, using canard makes a longer CCT, and LEF can reduce CCT by reducing the drag coefficient, both coincide with superiority results.

3.3 Takeoff and Landing

3.3.1 Superiority Evaluation

The weighting parameters a_L, a_m, a_{rl} for takeoff and landing before touchdown are selected as 0.4, 0.4 and 0.2 respectively. The weighting parameters a_L, a_D for landing after touchdown can be selected based on the braking friction, and are set to 0.4 and 0.6 in our simulation. Since the forces and moments generated by thrust vectoring do not vary with the velocity, $V_R = 60$ m/s is taken as the reference speed in our simulation.

For takeoff and landing, the elevons are considered as on elevon deflecting

$$\delta_e = (\delta_{roe}+\delta_{rie}+\delta_{lie}+\delta_{loe})/4$$

Choosing elevon as the reference control effector, the superiority parameters at takeoff speed are given in Tables 6 to 8.

Table 6 Superiority parameters for takeoff

Control effector	$R_{L\delta i}$	$R_{m\delta i}$	$R_{rl\delta i}$	$P_{\delta i}$
Canard	0.032	0.35	1	0.353
Elevon	1	-1	1	0.2
LEF	-0.024	-0.022	0.4	0.0615
TV (+)	0.43	-6.53	0.5	-2.34
TV (-)	-0.43	6.53	0.5	2.54

Table 7 Superiority parameters for landing (before TD)

Control effector	$R_{L\delta i}$	$R_{m\delta i}$	$R_{rl\delta i}$	$P_{\delta i}$
Canard	0.0323	0.35	1	0.353
Elevon	1	-1	1	0.2
LEF	-0.024	-0.022	0.4	0.06
TV (+) Idle	0.04	-0.61	0.5	-0.13
TV (-) Idle	-0.04	0.61	0.5	0.33
TV (+) Max	0.43	-6.53	0.5	-2.34
TV (-) Max	-0.43	6.53	0.5	2.54

Table 8 Superiority parameters for landing (after TD)

Control effector	$R_{L\delta i}$	$R_{D\delta i}$	$P_{\delta i}$
Canard (+)	-0.056	0.57	0.319
Canard (-)	0.032	0.6	0.373
Elevon (+)	-1	1	0.2
Elevon (-)	1	1	1
TV (+)	-0.04	0.02	-0.004
TV (-)	0.04	0.02	0.028

If the TV nozzle deflects upward during takeoff and landing before touchdown, it will generate significant noseup pitching moment, and elevon will be allowed to deflect a larger downward angle to increase the lift coefficient. If TV nozzle deflects upward during landing after touchdown, it will increase the landing gear reaction and friction forces.

From the highest superiority to the lowest, the control effector sequence for takeoff is TV (upward), canard, elevon, and leading edge flap. The sequence for landing before touchdown is the same as takeoff, but the superiority parameters are different because of variations in thrusts. The sequence for landing after touchdown is elevon (upward), canard (upward) and TV (upward).

3.3.2 Simulation Verification

The control requirements for takeoff and landing are high; however, because of the low dynamic pressure and control effectiveness, single control effector can’t satisfy such control requirements. Therefore, the superiorities will be validated by comparing takeoff and landing performances for control effectors sets with optimized control allocation. Since elevons have to be used as high-lift devices, their superiority parameters will not be compared.

Table 9 Simulation results of takeoff performance

Control Effector Sets	Liftoff Speed (m/s)	Ground Run Distance (m)
$\delta_e+\delta_c+\delta_{le}$	82.19	391.75
$\delta_{tv}+\delta_e+\delta_{le}$	77.18	325.51
$\delta_{tv}+\delta_e+\delta_c+\delta_{le}$	74.16	301.02
$\delta_{tv}+\delta_e+\delta_c$	74.02	297.84

Table 10 Landing performance before TD ($\alpha=10°$)

Control Effector Sets	Touchdown Speed (m/s)	
	Idle thrust	Maximum thrust
$\delta_e+\delta_c+\delta_{le}$	63.3142	63.3142
$\delta_{tv}+\delta_e+\delta_{le}$	72.0698	58.5872
$\delta_{tv}+\delta_e+\delta_c+\delta_{le}$	61.9142	55.0671
$\delta_{tv}+\delta_e+\delta_c$	60.6688	54.4587

As shown in table 9 and 10, TV (up) can increase the takeoff and landing (before touchdown) performances effectively, then canard and LEF. This agrees well with the trends of the superiority parameters.

Table 11 gives the simulation results of landing after touchdown. The reference touchdown speed is 48m/s; the braking friction factor is 0.4, and rolling friction factor is 0.02.

Table 11 Landing performance after TD

Control Effector	Landing Ground Roll (m)
No Control Deflection	330.5
Elevon (up to max)	277.6
Canard (up to max)	301.2
TV (up to max)	316.9
Elevon + Canard + TV	249.9

The simulation results of landing ground roll agree well with the trends of the superiority parameters.

4 Conclusion

In this paper, a control effector superiority evaluation method is proposed based on the performance requirements.

The control effectors superiority evaluating method can be used to identify the control effectors participated in control, which can simplify the control allocation design as well as ensure the performance requirements.

The simulation results show that the evaluation model formalized in this paper can efficiently make use of performance potentials of the target aircraft.

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