Chinese Journal of Aeronautics, (2017), 30(3): 881–897

Chinese Society of Aeronautics and Astronautics
& Beihang University

Chinese Journal of Aeronautics

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Suggestion for aircraft flying qualities requirements of a short-range air combat mission

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Received 31 May 2016; revised 30 August 2016; accepted 3 January 2017
Available online 20 April 2017

KEYWORDS

Acquisition;
Flying qualities of fighter aircraft;
Mission requirements;
Multi-axis task;
Short-range air combat;
Tracking

Abstract Owing to the lack of a direct link with the operations in short-range air combat, conventional aircraft flying qualities criteria are inappropriate to guide the design of a task-tailored flight control law. By applying the mission-oriented flying qualities evaluation approach, various aircraft with different control law parameters are evaluated on a ground-based simulator. This paper compares the evaluation results with several conventional flying qualities criteria, and discusses the appropriate parameter combination to reflect the flying qualities requirements of short-range air combat. The comparison and analysis show that a short-range air combat mission requires a higher minimum short period mode natural frequency and a smaller maximum roll mode time constant, and allows a lower minimum pitch attitude bandwidth and a higher maximum short period mode damp ratio than those of conventional flying qualities criteria. Furthermore, a combination of the pitch attitude bandwidth, the pitch attitude magnitude at the bandwidth frequency, and the pitch attitude transfer function gain can define the flying qualities requirements of short-range air combat. The new metric can successfully predict the flying quality levels of aircraft in a short-range air combat mission.

1. Introduction

In a short-range air combat mission, a fighter's main task is target acquisition and tracking by multi-axis maneuvers.[1] Based on this feature of short-range air combat, aircraft dynamic characteristics can be optimized to achieve the optimal flying qualities for short-range air combat and enhance the air combat capability.[2,3] As design criteria, the flying qualities requirements of a short-range air combat mission are necessary for designing short-range air combat task-tailored flight control systems. However, the conventional criteria in flying qualities specifications such as MIL-F-8785C[4] and MIL-HDBK-1797A[5] need to give consideration to various flight missions that belong to the same flight phase and lack a direct link with a short-range air combat mission. Moreover, most criteria are intended to be applied to one axis at a time and emphasize small-amplitude control. They are different from the flying qualities requirements of a short-range air combat mission which consists of violent multi-axis maneuvers, Therefore, it is difficult to guide the design of a task-tailored flight

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Peer review under responsibility of Editorial Committee of CJA.

ELSEVIER Production and hosting by Elsevier

http://dx.doi.org/10.1016/j.cja.2017.03.004
1000-9361

control law by the common flying qualities criteria,[6] and it is necessary to investigate the specific flying qualities requirements of a short-range air combat mission.

To solve this problem, aircraft flying qualities in short-range air combat need to be evaluated accurately. The mission-oriented flying qualities evaluation approach directly relates to a specific mission and can be applied to multi-axis flying qualities evaluation, so the flying qualities of an aircraft in a specific mission can be evaluated accurately by this approach.[7–10] Thus, by selecting the maneuvers that directly reflect the short-range air combat mission, mission-oriented flying qualities evaluation can be conducted. Based on the evaluation results, the differences between the aircraft flying qualities requirements of the short-range air combat mission and the conventional flying qualities criteria can be obtained.

According to the mission-oriented flying qualities evaluation approach, flying qualities criteria for a high angle of attack aircraft were studied in Ref.[11]. The multi-axis mission-oriented flying qualities evaluation approach is also applied to evaluate the handling qualities effects of longitudinal and lateral coupling and the use of a rotorcraft flying qualities specification for fixed-wing aircraft.[12] However, little quantitative research has been performed on the flying qualities requirements of a short-range air combat mission. Therefore, we will attempt to obtain the flying qualities requirements for highly-augmented aircraft to accomplish multi-axis acquisition and tracking in short-range air combat.

In this paper, the crossing target acquisition and tracking (CTAT) task and the multi-axis HUD tracking (MAHT) task are selected as the demonstration maneuvers. Mission-oriented flying qualities evaluation is then conducted on a ground-based simulator. Based on the comparison between the evaluation results and several frequently used flying qualities criteria, the differences between the flying qualities requirements of a short-range air combat mission and the conventional criteria are analyzed. The flying qualities parameters that can represent the flying qualities requirements of the short-range air combat mission are put forward, and the quantitative limits of the parameters for the configurations evaluated are established. The law of flying qualities requirements of the short-range air combat mission revealed by this paper can be applied to flying qualities evaluation, design of task-tailored flight control laws for fighters, and short-range air combat efficiency evaluation.

2. Flying qualities evaluation approach for a short-range air combat mission

To conduct mission-oriented flying qualities evaluation, the first step is to design the demonstration maneuvers that are related to the operational use of an aircraft. The test aircraft is then evaluated by flying in the demonstration maneuvers with a pilot in the loop. Finally, flying qualities are evaluated based on flight data, pilot comments, and ratings.[13] Consequently, to evaluate the flying qualities of the aircraft in short-range air combat by the mission-oriented flying qualities evaluation approach, it is important that the demonstration maneuvers can reflect the main maneuver characteristics and flying qualities requirements of a short-range air combat mission.

2.1. Selection of demonstration maneuvers

The main task objectives of short-range air combat are rapid gross acquisition and continuous fine tracking of targets by multi-axis maneuvers. Thus, the demonstration maneuvers should be constituted by the maneuver elements of multi-axis acquisition and tracking, and there should be a coverage of moderate and large maneuver amplitudes.

In the set of mission task elements (MTEs) that have been developed for mission-oriented flying qualities evaluation, the CTAT task and the MAHT task are multi-axis maneuvers that contain tracking and acquisition elements.[14] As a large-amplitude maneuver, the CTAT task can check the ability to rapidly roll into the maneuver plane, pull to a high angle of attack (AOA) to capture a target, rapidly reverse the pitch rate, and track the target by longitudinal and lateral maneuvers.[13] The MAHT task consists of moderate-amplitude maneuvers, but it requires more frequent and sudden control changes than the CTAT task.[5]

Hence, by synthetically using the CTAT task and the MAHT task, multi-axis acquisition and tracking flying qualities in short-range air combat can be comprehensively evaluated with different maneuver amplitudes and control change frequencies. Since short-range air combat consists mostly of longitudinal and lateral maneuvers and the yaw axis control plays a main role in roll coordination, these two demonstration maneuvers are both set for longitudinal and lateral flying qualities evaluation. The specific maneuvers are as follows.

(1) Crossing target acquisition and tracking[13]

The CTAT task can be used to evaluate the overall longitudinal and lateral flying qualities, and reveal potential PIO tendencies of an aircraft in a violent maneuver with a moderately high AOA. In the task, a target begins with a level flight whose heading is perpendicular to that of the test aircraft. After passing above the test aircraft, the target begins a 5–6 g level turn into the test aircraft. At the same time, the test aircraft pilot pulls and rolls into the target maneuver plane and aggressively acquires the target within a 30 mil reticle. After the capture is completed, the maneuver requires the test aircraft pilot to push to unload rapidly and laterally track the target while reversing the roll attitude. The maneuver then transitions to a pitch tracking. After achieving enough tracking time, the pilot unloads the test aircraft to break off the task.

(2) Multi-axis HUD tracking[5]

The MAHT task can be used to precisely evaluate the longitudinal and lateral flying qualities of an aircraft during attitude tracking. The maneuver requires the test aircraft pilot to track the sequence of pitch and roll attitude commands.

By comparison, it can be observed that both of these two tasks mainly evaluate attitude control characteristics. The differences between them can be discussed in terms of different axes. Firstly, in the pitch axis, the CTAT task is mainly concerned with the left district of the flight envelop. It requires the test aircraft to pull to a high AOA for an acquisition, and the relative position between the test aircraft and the target is stable during pitch tracking. However, the MAHT task is mainly concerned with the aircraft handling qualities around the corner velocity. It requires the test aircraft to track the sequence of attitude commands with a small AOA but frequent and sudden attitude changes. Secondly, in the roll axis, because the roll is about the stability axis, the lateral acquisition and tracking required by the CTAT task are presented as a lateral movement of the target beside the reticle. However, in the MAHT task, the lateral tracking target is a roll attitude command that makes it easier to accomplish the maneuver. In summary, the CTAT task and the MAHT task can evaluate the flying qualities of an aircraft in short-range air combat from different aspects. Conclusions about flying qualities requirements based on these two maneuvers respectively can be compared to verify each other. They can also be integrated to reflect the flying qualities requirements of a short-range air combat mission.

2.2. Evaluation aircraft model

This paper is developed for Class IV aircraft,[5] and flying qualities evaluation is based on the nonlinear model of an F-16/MATV aircraft[15,16] with a model reference nonlinear dynamic inversion flight controller.[17–19] The F-16/MATV aircraft is equipped with multi-axis thrust vectoring and can maneuver with a high AOA. The nonlinear aircraft model is created using geometric and aerodynamic data from Ref.[16]. The actuators of the control surfaces are modeled as first-order low-pass filters. The fixed gain and saturation limits in the range and deflection rate are from Ref.[15].

The model reference nonlinear dynamic inversion flight controller is from Ref.[17]. The flight controller contains transfer-function-based reference models, a dynamic inversion to compute the surface positions to achieve the desired aircraft dynamics, and a PI compensator to drive down the error between the reference model dynamics and the actual dynamics. The dynamic inversion and PI compensator can guarantee that the closed-loop dynamic characteristics of the aircraft are very similar to the reference models. Therefore, the handling characteristics can be adjusted in a wide range by changing the 3-axis reference models.[18] The pitch reference model is the short period transfer function:

$$\frac{q^{\text{RM}}}{w_y}=\frac{\overline{K}_q\left(s+\dfrac{\overline{\varpi}_{\text{sp}}^2}{(V/g)\cdot\overline{\text{CAP}}}\right)}{s^2+2\overline{\xi}_{\text{sp}}\overline{\varpi}_{\text{sp}}s+\overline{\varpi}_{\text{sp}}^2} \tag{1}$$

where q^{RM} is the reference model response to the pitch stick commands w_y, while $\overline{K}_q$, $\overline{\varpi}_{\text{sp}}$, $\overline{\xi}_{\text{sp}}$, and $\overline{\text{CAP}}$ are the controller parameters of the pitch axis, V is the aircraft flight velocity, s is the complex variable in transfer function.

The roll reference model is the first-order roll mode transfer function:

$$\frac{p_{\text{s}}^{\text{RM}}}{w_x}=\frac{\overline{K}_{\text{p}}}{\overline{T}_{\text{r}}s+1} \tag{2}$$

where p_{s}^{RM} is the reference model response to the roll stick commands w_x, while $\overline{K}_{\text{p}}$ and $\overline{T}_{\text{r}}$ are the controller parameters of the roll axis.

The rudder pedal w_z is used to generate a desired lateral acceleration. The yaw reference model transfer function is

$$r_{\text{s}}^{\text{RM}}=\frac{g}{V}[\overline{K}_{ny}(\overline{K}_z w_z-n_y)+\sin\phi\cos\theta]\frac{\overline{\varpi}_{\text{r}}}{s+\overline{\varpi}_{\text{r}}} \tag{3}$$

where r_{s}^{RM} is the reference model response to the rudder pedal commands w_z, while $\overline{K}_{ny}$, $\overline{K}_z$, and $\overline{\varpi}_{\text{r}}$ are the controller parameters of the yaw axis, ϕ, θ, ψ are the roll angle, pitch angle, and yaw angle, n_y is the lateral acceleration.

The PI compensator parameters are the functions of the reference model parameters, and the PI compensator structure can be seen in Ref.[17]. Thus, the closed-loop aircraft dynamic characteristics are fixed only by the reference models parameters.

Then evaluations of F-16/MATV flying qualities are conducted on a ground-based simulator by pilots. The simulator is equipped with a side stick using stick position commands. Thus, the conclusions given by this paper are applicable only to side stick controllers and stick position commands. The validity of the results for center stick controllers or stick force commands is undetermined.

2.3. Flying qualities evaluation scale

After flight tests on the simulator, both engineers and pilots will use the Cooper-Harper rating (CHR) scale[20] and the PIO rating (PIOR) scale[21] to evaluate the aircraft flying qualities and PIO tendency respectively based on the task performance and pilot workload.

The aircraft characteristics performed in the CTAT task mainly include the rapidity and stability of acquisition, as well as the accuracy and stability of tracking.[13] The rapidity and stability of acquisition are represented by the time to acquire and the number of overshoots, respectively. The accuracy and stability of tracking are represented by the proportion of the aiming time to the time during tracking. Aiming time is defined as the time that is taken to maintain a target within the reticle with a certain radius. Performance standards contain desired performance standards and adequate performance standards. If adequate performance standards cannot be achieved, the performance level is unacceptable. The performance standards of the CTAT task are given by Ref.[13] which are shown in Table 1.

The capture time depends on the maneuver setup and the aircraft. For a specific aircraft class and maneuver setup, the performance level of the capture time needs to be evaluated by a pilot. Thus, pre-evaluation is conducted. In pre-evaluation, 22 configurations are tested. The pilots accomplishes the task and evaluates the capture time. If the pilot observes a desired/adequate capture time, he/she will label the length of the capture time as short/medium. If the pilot

Table 1 Performance standards for CTAT task.

Performance level	Capture time (s)	Overshoot times	Time ratio within the 30 mil reticle (%)
Desired	Desired time	≤1	≥50
Adequate	Adequate time	≤2	≥10

considers that the capture time is unacceptable, or the task can't be accomplished, the length of the capture time will be labeled as long. A specific capture time standard is ascertained based on the actual capture time and pilot comments. The distribution of the actual capture time which is labeled the same as the pilot comments is shown by the boxplot in Fig. 1. The statistical meaning of the boxplot can be seen in Ref.[22].

It can be observed that the pre-evaluation results cover all of the three length levels of the capture time in Fig. 1. In addition, the actual capture times are statistically different between the three length levels. Therefore, based on the pre-evaluation results, the desired and adequate capture time standards are 10 s and 15 s, respectively.

In the MAHT task, the task performance is the accuracy of tracking, and the index parameter is the size of the reticle within which the target attitude commands can be kept for 50% of the task time. The pitch axis performance standards are given by Ref.[12]. The desired pitch standard boundary is 10 mil, and the adequate pitch standard boundary is 20 mil. However, they are not the specific roll standard boundaries in Ref.[12]. Thus, pre-evaluation for the MAHT task is conducted.

In pre-evaluation, pilots give some brief comments on the aircraft handling characteristics by accomplishing the task. These comments are grouped into three categories. The first group is defined as "satisfactory characteristics and minimal or moderate pilot compensation is required". The second group is defined as "adequate characteristics and considerable or extensive pilot compensation is required". The last group is defined as "unacceptable characteristics and considerable or extensive pilot compensation is required for control". The three groups of comments are labeled with S, A, and C, respectively. The desired performance can only be achieved by an aircraft with satisfactory characteristics, and an aircraft with unacceptable characteristics cannot achieve the adequate performance. Based on this point, the task performance standards can be defined by pilot comments and the actual task performance.

In pre-evaluation, the performance standards require that the pitch and roll error limits are satisfied simultaneously. An alternative desired performance standard is constituted by a combination of a desired pitch tracking error limit of 10 mil and alternative desired roll tracking error limits of 3°, 4°, and 5°. An alternative adequate performance standard is constituted by a combination of an adequate pitch tracking error limit of 20 mil and alternative adequate roll tracking error limits of 4°, 6°, and 8°. 18 configurations are evaluated in pre-evaluation, and each configuration is evaluated twice. The proportion of time that is taken to maintain the errors within the performance standard to the task time is defined as the task time ratio. Therefore, there are 36 data points, and each point has one pilot comment and 6 different task time ratios for the 6 alternative performance standards respectively. The relationship between the pilot comment and the task time ratio for different performance standards is compared in Fig. 2. It can be seen that the figures are divided into 3 parts by the alternative performance standards. Each part is a boxplot to show the task time ratio distribution of the points with the same comments label. There are 19, 15, and 2 points in the groups with comments labels of S, A, and C, respectively.

Based on Fig. 2(a), only if the desired roll performance standard boundary is 4°, all of the aircraft with satisfactory characteristics can achieve the desired performance, and most of the aircraft with adequate characteristics can just achieve the adequate performance. Based on Fig. 2(b), it can be observed that an adequate roll performance standard of 4° is too strict, while 8° is too loose. Therefore, an adequate roll performance standard of 6° is suitable. The performance standards for the MAHT task are listed in Table 2.

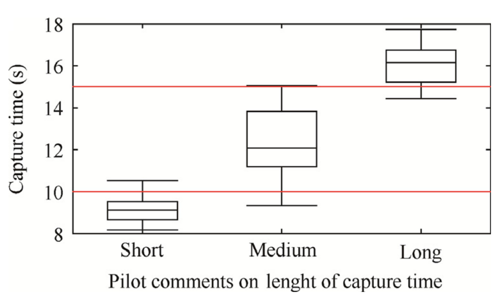


Fig. 1 Boxplot for actual capture time and pilot comments in pre-evaluation.

3. Flying qualities evaluation based on CTAT task

The flying qualities of the F-16/MATV aircraft in the CTAT task are evaluated firstly.

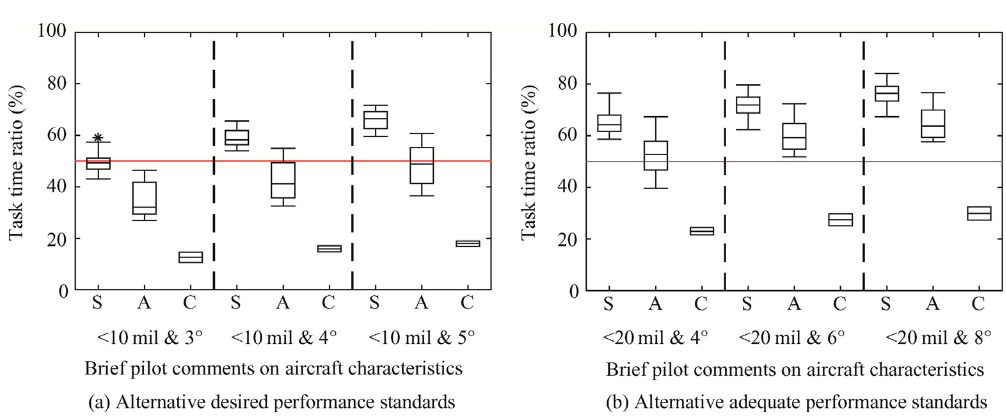


Fig. 2 Boxplot for comparison between alternative performance standards (mil means one-thousandth of an inch).

Table 2 Performance standards for MAHT task.

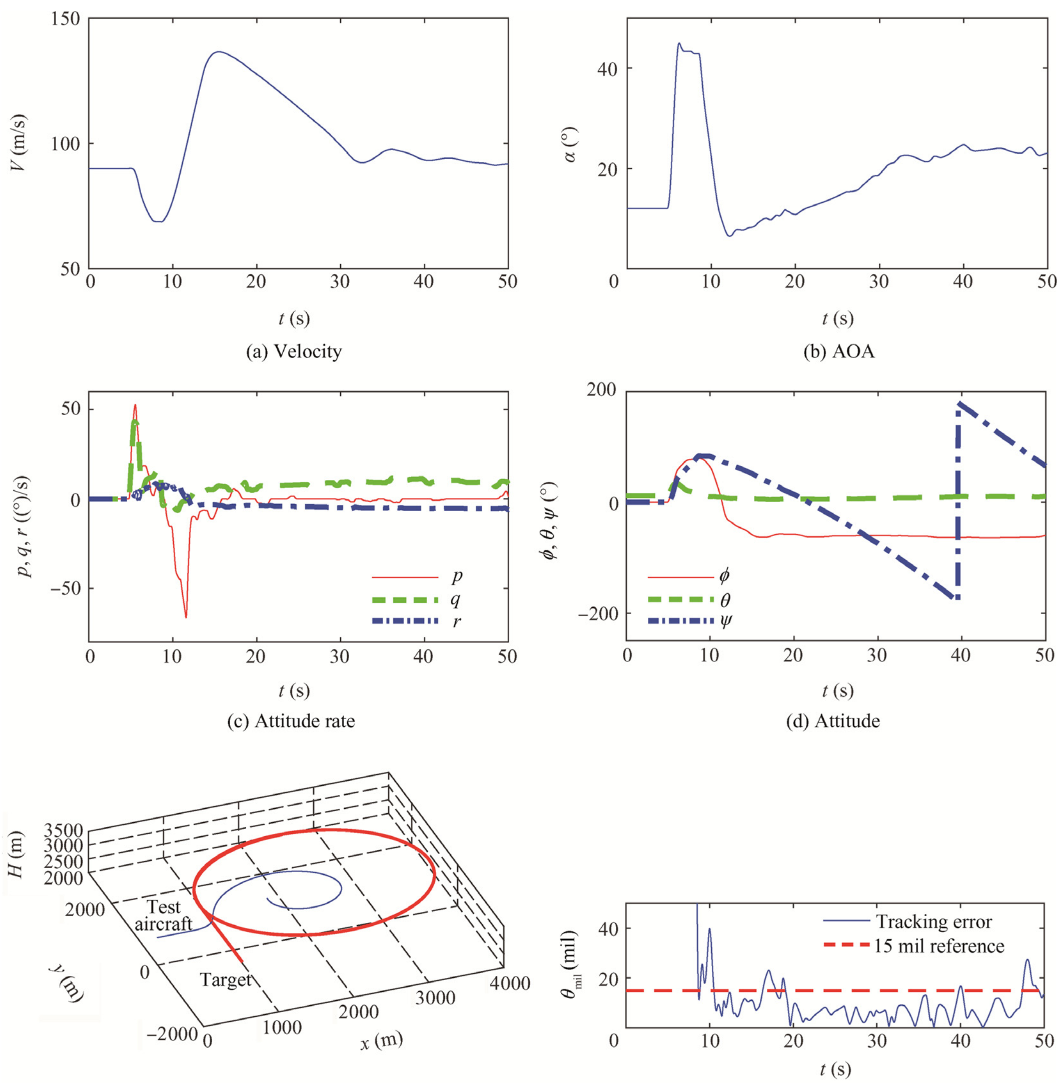
Performance level	Tracking error limit during 50% task time	
	Pitch attitude (mil)	Roll attitude (°)
Desired	≤10	≤4
Adequate	≤20	≤6

3.1. Evaluation case

The test aircraft flies at an initial velocity of 90 m/s and an altitude of 3000 m. The process of maneuvering can be found in Fig. 3, in while t is the time, V, α are the flight velocity and angle of attack, p, q, r are the roll rate, pitch rate, and yaw rate, ϕ, θ, ψ are the roll angle, pitch angle, and yaw angle, H is the flight altitude, x, y are the aircraft positions along the x-axis and y-axis respectively, and θ_{mil} is the aiming error.

It can be observed that the target begins a level turn after passing above the test aircraft. At the same time, the test aircraft pulls to an AOA of 45° to capture the target aggressively. After the first acquisition at approximately 8.6 s, the test aircraft rapidly unloads, reverses the roll attitude from 80° to −70°, laterally acquires the target at approximately 10.5 s, and then conducts fine tacking.

In the evaluation, the first capture is at 8.64 s, and the number of overshoots is one. The target is kept within the 15 mil reticle for 92.4% of the tracking time. Thus, the task performance level is evaluated as desired according to Table 1. The pilot comments are as follows: "Not very much pilot compensation was required. In the pitch axis, the control sensitivity was appropriate, and the initial response was about right. The aircraft was predictable, and there was no undesirable motion. In the roll axis, the initial response and predictability were good. It was easy to keep the target within the pipper. The roll control was slightly sensitive when I was reversing the roll attitude. No PIO tendency". The pilot gives a CHR of 2 and a PIOR of 1. Therefore, the test aircraft has Level 1 flying qualities.



(a) Velocity (b) AOA (c) Attitude rate (d) Attitude (e) Flight path of test aircraft and target (f) Aiming error

Fig. 3 Flight response and aiming error of test aircraft in CTAT task.

3.2. Flying qualities evaluation results of different configurations

Because the CTAT task is a multi-axis maneuver, the evaluation consists of longitudinal and lateral flying qualities evaluation.

3.2.1. Longitudinal flying qualities evaluation results

The longitudinal flying qualities evaluation is conducted under the condition that the roll mode time constant is maintained at 0.16 s. By adjusting the parameters of the pitch axis reference model, 68 configurations with different longitudinal dynamic characteristics are evaluated in the CTAT task. The longitudinal flying qualities parameters of the configurations that are obtained include the natural frequency of the short-period oscillation ω_{sp}, damping ratio of the short-period oscillation ξ_{sp}, control anticipation parameter CAP, pitch attitude zero of the short-period mode $1/T_{\theta 2}$, equivalent system gain for the short-period mode K_q , steady-state normal acceleration change per unit change in the angle of attack n_z/α, attitude bandwidth frequency $\omega_{\mathrm{BW}\theta}$, phase lag equivalent time delay τ_{p}, and pitch stick input to the attitude transfer function magnitude at the bandwidth frequency M_θ. Except for M_θ, the definitions and calculation methods of these parameters can be found in flying qualities specifications.[5]

As a control sensitivity metric, M_θ is defined as the value of the pitch attitude frequency-response magnitude at $\omega_{\mathrm{BW}\theta}$.[23] Because the value of M_θ is related to the unit of the stick input signals, the conclusions in this paper regarding the appropriate value for M_θ must be converted when it is applied to other aircraft. In this paper, the normalized stick position command signals used in the flying qualities evaluation experiments have a maximum value of 1. If the unit of the pitch angle is rad, for an aircraft with a maximum stick position of S_y, the conversion relation between its pitch attitude magnitude at the bandwidth frequency, $M_{\theta,S}$, and M_θ used in this paper can be written as $M_{\theta,S} = M_\theta - 20\lg S_y$. The flying qualities evaluation results and several longitudinal flying qualities parameters for the 68 configurations with different longitudinal dynamic characteristics are listed in Table 3. The CHR and PIOR are the average values.

3.2.2. Lateral flying qualities evaluation results

By adjusting the parameters of the roll axis reference model, 16 different lateral configurations with the longitudinal dynamic characteristics of CF-44 in Table 3 are evaluated in the CTAT task. The evaluation results and the roll mode time constant T_{r} for the 16 configurations are listed in Table 4.

4. Flying qualities evaluation based on MAHT task

Similarly, the flying qualities evaluation on the MAHT task is also based on the F-16/MATV aircraft with the model reference nonlinear dynamic inversion flight controller.

4.1. Evaluation case

The test aircraft flies at an initial velocity of 180 m/s and an altitude of 3000 m. The process of maneuvering can be found in Fig. 4, where ϕ_{c}, θ_{c} are the roll and pitch angle commands, respectively.

It can be observed that the AOA is within the range of low angles of attack. Attitude tracking effects can be observed in Fig. 4(c) and (d). The pitch attitude tracking error is kept within 10 mil for 69.51% of the task time, and for the roll axis, the tracking error is kept within 4° for 72.36% of the task time. The time is 52.47% of the task time which is taken to maintain the pitch attitude tracking error within 10 mil and the roll attitude tracking error within 4° at the same time. Based on a comparison with the performance standard in Table 2, the task performance level of this evaluation is evaluated as desired.

The pilot comments were as follows: "In the roll axis, the control sensitivity was appropriate. The aircraft was predictable, but there were some overshoots. A little compensation was required to obtain a high tracking accuracy. In the pitch axis, the aircraft was good, and it was easy to conduct precision tracking. There were no real undesirable motions". The pilot gives a CHR of 2.5 and a PIOR of 1. Therefore, the test aircraft has Level 1 flying qualities.

4.2. Flying qualities evaluation results of different configurations

Evaluation based on the MAHT task also consists of longitudinal and lateral flying qualities evaluation.

4.2.1. Longitudinal flying qualities evaluation results

By adjusting the parameters of the pitch axis reference model, 85 different longitudinal configurations with a fixed roll mode time constant of 0.125 s are evaluated in the MAHT task. The flying qualities evaluation results and the longitudinal flying qualities parameters of the 85 configurations are shown in Table 5.

4.2.2. Lateral flying qualities evaluation results

By adjusting the parameters of the roll axis reference model, 16 different lateral configurations with the longitudinal dynamic characteristics of HF-79 are evaluated in the MAHT task. The flying qualities evaluation results and the roll mode time constant T_{r} for the 16 configurations are listed in Table 6.

5. Longitudinal flying qualities requirements

After obtaining the flying qualities levels of different configurations based on the two demonstration maneuvers, this paper will compare these evaluation results with several conventional flying qualities criteria to analyze the differences between the flying qualities requirements of a short-range air combat mission and the conventional criteria. Based on the analysis and the pilot comments, flying qualities parameters that can represent the flying qualities requirements of a short range air combat mission will then be put forward. Because the CTAT task and the MAHT task evaluate aircraft flying qualities from different aspects, the flying qualities requirements of a short-range air combat mission consist of the intersection of the requirements of the two demonstration maneuvers. Firstly, the longitudinal flying qualities requirements are analyzed.

5.1. Comparison with conventional longitudinal flying qualities

The comparison between the mission-oriented flying qualities evaluation results and the conventional longitudinal flying

Table 3 Longitudinal pilot ratings and parameters in CTAT task.

No.	ω_{sp} (rad/s)	ξ_{sp}	CAP (g^{-2}·s^{-1})	$T_{\theta 2}$ (s)	K_q ((°)/s)	n_z/α (g/rad)	$\omega_{BW\theta}$ (rad/s)	M_θ (dB)	τ_p (ms)	CHR	PIOR
CF-1	0.5	0.8	0.4	14.3	1.4	0.7	0.9	3.5	32.1	8	3
CF-2	0.7	0.8	0.5	9.0	1.0	1.0	1.3	−4.9	33.0	7	3
CF-3	1.1	1.1	1.0	3.4	1.5	2.7	2.1	−12.0	24.0	6	3.5
CF-4	1.1	1.4	0.5	6.1	5.1	1.5	2.8	−6.7	24.0	5.5	3.5
CF-5	1.0	1.2	0.9	7.6	8.4	1.2	2.4	1.2	35.1	7	3
CF-6	1.0	1.2	0.1	0.9	3.1	10.1	0.9	7.3	33.2	8	3
CF-7	0.9	1.3	0.2	2.4	3.2	3.8	1.7	−3.1	34.1	6	1.5
CF-8	0.9	1.3	0.2	2.0	3.2	4.7	1.4	−0.4	33.9	7	3
CF-9	1.0	1.2	0.1	1.0	1.0	9.5	0.9	−2.3	32.3	8	3
CF-10	2.1	0.9	1.1	2.7	4.4	3.4	3.7	−11.3	24.0	6.5	3.5
CF-11	2.1	0.8	3.0	2.6	3.2	3.5	3.7	−14.2	24.0	6	3
CF-12	2.0	0.8	0.9	2.1	1.1	4.4	3.2	−20.9	34.7	7	1
CF-13	1.9	0.9	0.9	2.3	0.6	4.1	3.2	−26.9	37.7	7	1
CF-14	2.1	0.9	1.1	1.7	2.2	5.3	3.6	−17.2	24.0	5.5	3
CF-15	2.0	1.0	0.2	1.4	4.3	6.6	3.3	−10.4	15.0	5	3.5
CF-16	2.1	0.9	2.4	4.4	7.4	2.1	4.0	−8.2	24.0	7.5	4
CF-17	2.1	1.1	2.2	4.4	8.6	2.1	4.5	−9.6	24.0	8.5	4.5
CF-18	2.0	1.2	0.9	1.0	3.1	9.7	3.3	−14.1	24.0	5	3
CF-19	1.9	1.5	1.1	2.2	2.7	4.2	4.6	−20.9	24.0	3.5	3
CF-20	2.2	1.3	0.8	1.6	4.5	5.6	4.6	−16.8	24.0	2.5	1
CF-21	2.0	1.4	0.3	0.5	3.2	19.0	1.7	−5.3	25.0	6	3.5
CF-22	2.2	1.4	0.9	1.7	5.5	5.3	4.6	−14.9	24.0	3.5	2
CF-23	1.9	1.5	1.0	2.5	1.2	3.6	4.1	−26.8	39.3	7	1
CF-24	1.9	1.4	0.9	2.4	1.7	3.8	4.1	−23.3	35.4	4.5	1
CF-25	2.0	1.5	1.0	2.4	2.4	3.8	4.1	−20.8	40.3	3	1
CF-26	3.1	0.6	1.9	1.1	3.8	8.6	4.1	−12.6	25.0	5	3.5
CF-27	3.1	0.6	2.3	0.5	1.9	17.4	3.5	−15.1	27.0	5	3.5
CF-28	3.1	0.6	0.5	1.6	5.3	5.8	4.3	−10.4	25.0	7	4
CF-29	3.2	0.9	1.0	1.0	3.8	9.3	4.9	−17.8	24.0	3.5	1.5
CF-30	3.0	0.9	0.8	1.6	5.3	5.7	5.2	−15.7	24.0	3.5	3
CF-31	3.3	0.9	1.9	1.6	12.3	5.7	4.8	−7.7	41.9	7	3
CF-32	3.2	1.3	1.6	1.5	5.5	6.3	6.6	−20.8	23.0	2	1
CF-33	3.8	1.8	0.7	2.5	14.8	3.7	10.2	−20.1	22.0	4	2
CF-34	4.1	0.5	0.7	0.2	3.1	40.2	3.8	−11.1	32.0	4	3
CF-35	4.0	0.5	1.8	0.3	1.7	36.2	3.8	−17.1	32.0	4	2.5
CF-36	4.2	0.5	0.2	0.2	5.3	40.1	3.8	−6.6	32.0	5	4
CF-37	3.8	0.5	0.6	0.4	8.3	25.8	3.9	−3.5	52.9	6	2
CF-38	3.9	0.5	0.5	0.3	8.9	29.2	3.9	−2.2	45.3	6.5	2
CF-39	3.9	0.5	0.5	0.3	10.5	28.1	3.9	−1.0	48.5	7	3
CF-40	4.6	1.2	1.8	1.0	6.3	9.1	8.3	−23.8	23.0	3	1
CF-41	4.1	1.6	1.1	0.6	4.2	15.1	6.8	−26.5	24.0	2	1
CF-42	4.2	1.2	1.3	2.2	14.0	4.2	8.8	−16.6	23.0	6.5	3
CF-43	4.7	1.3	0.7	1.1	8.8	8.7	8.3	−21.7	23.0	2.5	1
CF-44	4.2	1.2	0.6	0.5	5.5	19.8	6.8	−22.0	24.0	2	1
CF-45	3.9	1.7	1.3	0.8	2.4	12.0	6.4	−31.4	45.8	6	1
CF-46	3.7	2.1	1.5	1.0	1.9	8.9	6.4	−34.9	55.8	7	1
CF-47	3.3	1.8	1.2	1.0	3.0	9.2	6.4	−28.9	40.8	4	1
CF-48	4.0	1.2	4.3	2.5	21.1	3.7	8.4	−12.2	13.9	7	2
CF-49	4.0	2.2	4.7	2.7	2.3	3.4	11.8	−39.2	11.7	7	1
CF-50	4.2	2.0	4.4	2.3	3.3	4.0	11.8	−35.7	11.0	7	1.5
CF-51	4.1	2.0	4.4	2.3	5.5	3.9	11.8	−31.2	10.6	6.5	1
CF-52	4.1	2.0	0.8	2.3	6.2	4.0	12.2	−30.3	21.0	5	2
CF-53	4.3	2.0	1.8	2.2	9.9	4.1	12.2	−26.7	21.0	3	1.5
CF-54	4.1	2.0	1.3	2.2	13.3	4.2	12.2	−23.5	21.0	3.5	2
CF-55	4.3	2.0	1.1	2.2	16.2	4.3	12.2	−22.3	21.0	4	3
CF-56	5.1	2.0	4.2	1.5	9.4	6.3	14.0	−29.0	6.4	7	2.5
CF-57	5.9	0.5	0.9	0.7	9.0	12.6	7.2	−13.7	25.0	4	3
CF-58	5.7	0.5	3.0	0.9	14.4	10.6	6.9	−8.5	36.9	5	2.5
CF-59	6.0	0.7	1.6	0.3	4.2	30.1	6.8	−22.1	26.0	2.5	1
CF-60	5.6	0.7	0.6	0.3	5.4	28.9	6.8	−19.0	26.0	2	1
CF-61	5.9	2.2	4.5	1.2	14.4	7.8	14.9	−27.5	5.1	5	2.5
CF-62	9.6	0.4	3.0	0.1	2.7	85.8	7.3	−22.5	35.0	2.5	1
CF-63	8.4	0.4	0.8	0.3	9.1	30.8	9.4	−17.0	27.0	5	3

(*continued on next page*)

Table 3 (*continued*)

No.	ω_{sp} (rad/s)	ξ_{sp}	CAP ($g^{-2}\cdot s^{-1}$)	$T_{\theta 2}$ (s)	K_q ((°)/s)	n_z/α (g/rad)	$\omega_{BW\theta}$ (rad/s)	M_θ (dB)	τ_p (ms)	CHR	PIOR
CF-64	8.6	0.4	0.9	0.1	5.7	80.0	7.3	−16.5	35.0	3	1.5
CF-65	8.1	0.7	0.7	0.9	15.8	10.6	11.6	−17.4	23.0	9	5
CF-66	8.5	0.6	2.7	0.3	7.8	32.0	10.3	−22.4	25.0	3.5	1.5
CF-67	8.2	0.8	1.3	0.1	3.1	79.9	7.5	−25.6	29.0	2	1
CF-68	8.1	1.2	0.6	0.1	5.3	78.0	7.1	−24.2	26.0	3	1

Table 4 Lateral pilot ratings and parameters in CTAT task.

No.	T_r (s)	CHR	PIOR	No.	T_r (s)	CHR	PIOR
CF-69	1.248	8	4.5	CF-77	0.147	2	1
CF-70	0.982	7.5	4.5	CF-78	0.137	3	1
CF-71	0.710	6	4	CF-79	0.123	4.5	2.5
CF-72	0.486	5	3	CF-80	0.097	4.5	2.5
CF-73	0.315	5	3.5	CF-81	0.082	5	3
CF-74	0.244	5	3	CF-82	0.063	5	3
CF-75	0.193	4	2.5	CF-83	0.031	6.5	3
CF-76	0.171	2.5	1	CF-84	0.023	6.5	3.5

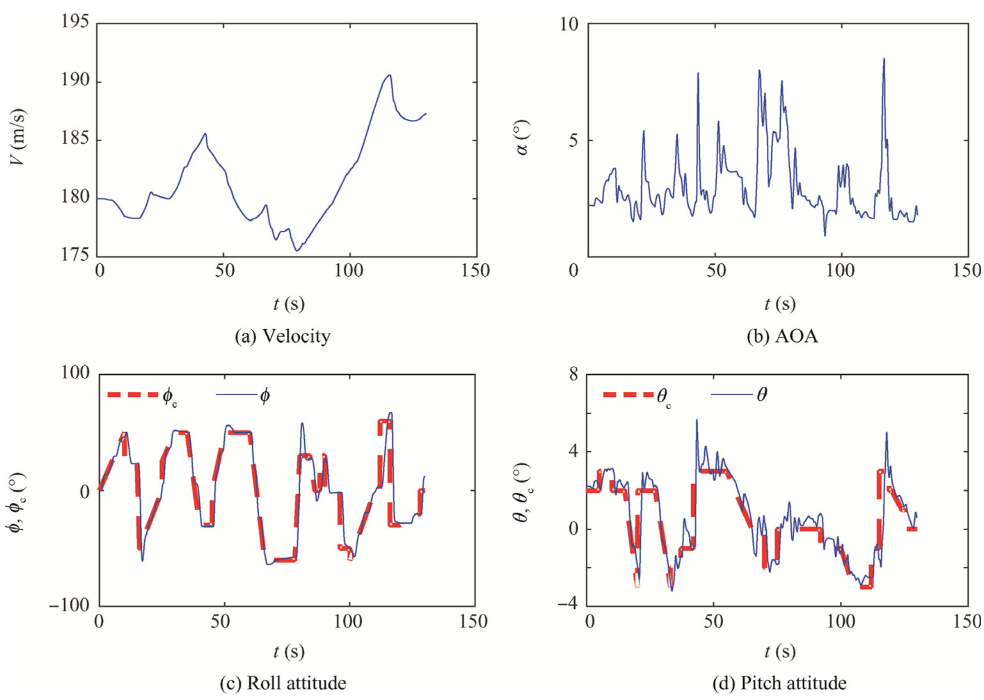


Fig. 4 Attitude commands and flight response of test aircraft in MAHT task.

qualities criteria will be analyzed in three aspects: the rapidity and coordination of the initial response, the coordination between the attitude and path responses, and the stability of the attitude response.

5.1.1. Requirements for rapidity and coordination of initial response

ω_{sp} can reflect the rapidity of the initial response.[5] The comparison between the mission-oriented flying qualities evaluation results and the ω_{sp} vs n_z/α criterion for Category A flight phases and Class IV aircraft is shown in Fig. 5.

It is shown that the two demonstration maneuvers require the same minimum allowable ω_{sp} of 2 rad/s in Fig. 5. Therefore, a short-range air combat mission requires that ω_{sp} shall be larger than 2 rad/s, and this requirement is stricter than the conventional longitudinal flying qualities criterion, which requires ω_{sp} to be larger than 1 rad/s. This strictness can be attributed to the fact that in short-range air combat, an air-

Table 5 Longitudinal pilot ratings and parameters in MAHT task.

No.	ω_{sp} (rad/s)	ξ_{sp}	CAP (g^{-2}·s^{-1})	$T_{\theta 2}$ (s)	K_q ((°)/s)	n_z/α (g/rad)	$\omega_{BW\theta}$ (rad/s)	M_θ (dB)	τ_p (ms)	CHR	PIOR
HF-1	1.0	0.7	1.2	22.0	2.9	0.8	1.8	−1.2	48.4	7	3
HF-2	1.0	0.8	1.4	14.7	1.4	0.7	1.8	−7.9	47.4	7	3
HF-3	1.0	0.8	0.7	14.1	1.9	1.3	1.8	−5.0	44.8	7	3
HF-4	1.0	1.0	1.0	18.1	18.1	1.0	2.1	−25.0	48.0	7	2
HF-5	1.0	1.0	1.0	18.3	18.3	1.0	2.1	−20.6	48.2	7	2.5
HF-6	1.0	1.0	1.0	18.4	18.4	1.0	2.1	−14.6	47.7	6	3
HF-7	1.0	1.0	1.1	18.6	1.5	1.0	2.1	−11.0	50.3	7	2.5
HF-8	1.5	0.8	0.8	7.6	5.5	2.4	2.6	−3.0	37.0	9	4.5
HF-9	1.6	1.4	0.7	7.7	5.9	2.4	3.7	−10.6	35.0	6	2.5
HF-10	1.7	2.0	0.7	7.8	6.4	2.4	4.7	−14.6	35.0	5.5	3
HF-11	2.1	1.1	0.6	3.5	2.3	5.2	4.0	−19.5	36.0	6.5	3
HF-12	2.1	1.1	0.6	3.6	1.6	5.1	4.0	−22.4	36.0	5.5	2
HF-13	2.1	1.0	0.9	4.9	3.1	3.7	3.9	−16.1	36.0	6	3
HF-14	2.1	0.7	1.3	5.5	3.1	3.4	3.3	−11.4	51.4	6	2
HF-15	2.0	0.8	0.8	3.7	0.5	5.0	3.3	−27.5	49.2	7	1
HF-16	2.0	0.8	0.8	3.9	1.0	4.7	3.3	−21.4	49.1	6	1
HF-17	2.1	0.8	0.8	3.6	1.5	5.1	3.3	−17.9	48.6	5	1
HF-18	2.1	1.1	0.9	5.4	2.1	3.4	4.1	−20.2	36.0	5	2
HF-19	2.2	1.2	0.9	3.6	0.6	5.2	4.2	−33.0	54.1	7	1
HF-20	2.0	1.5	1.1	4.8	1.2	3.8	4.2	−26.9	60.9	4	1
HF-21	2.1	1.4	0.6	3.3	1.6	5.6	4.9	−26.7	35.0	3.5	1
HF-22	2.1	1.4	0.6	3.3	2.5	5.6	4.9	−22.3	35.0	3	1
HF-23	2.1	1.4	0.6	3.3	4.1	5.6	4.9	−18.2	35.0	3.5	1.5
HF-24	2.1	1.4	0.6	3.3	5.1	5.6	4.9	−16.3	35.0	3.5	1.5
HF-25	3.1	0.6	0.4	1.0	1.9	18.4	4.1	−19.1	38.0	6	3
HF-26	3.1	0.9	0.7	1.9	3.3	9.7	5.3	−20.2	35.0	3.5	1.5
HF-27	3.2	0.9	1.1	2.9	5.2	6.3	5.4	−16.6	35.0	4	2
HF-28	3.1	1.2	0.9	1.7	1.7	10.9	5.7	−42.7	40.2	7	1
HF-29	3.0	1.2	0.9	1.8	1.8	10.2	5.7	−38.3	40.3	6.5	1
HF-30	3.0	1.1	0.8	1.7	1.7	11.0	5.7	−32.3	35.0	4	1
HF-31	3.1	1.2	0.9	1.6	1.6	11.2	5.7	−28.7	39.4	3.5	1.5
HF-32	3.6	0.5	0.3	0.6	5.8	30.6	4.1	−7.8	40.0	6	3
HF-33	3.6	0.5	0.8	1.4	5.6	13.1	4.6	−10.1	38.0	5	2
HF-34	3.6	0.5	1.9	3.6	5.7	5.1	4.8	−10.9	37.0	6.5	2.5
HF-35	3.6	0.3	2.5	3.7	5.5	5.0	4.3	−6.2	49.6	6.5	4
HF-36	3.5	0.3	2.5	3.7	7.0	5.0	4.3	−4.1	49.3	8	4
HF-37	3.7	1.1	0.3	0.6	6.0	30.6	5.5	−17.4	36.0	3.5	2
HF-38	3.6	1.1	0.7	1.5	5.9	12.2	6.5	−19.5	35.0	3	1
HF-39	3.8	1.0	3.0	3.8	3.5	4.8	6.2	−23.1	46.9	3.5	1
HF-40	4.1	1.2	1.7	3.6	7.3	5.1	6.9	−20.2	34.0	3.5	1.5
HF-41	4.1	1.7	0.6	1.4	7.1	13.1	8.2	−24.3	33.0	3.5	1
HF-42	4.3	1.9	1.5	3.6	8.1	5.1	8.6	−24.8	32.0	3	1
HF-43	3.6	1.8	2.0	4.7	13.5	3.9	9.7	−19.2	32.0	3	1
HF-44	4.2	0.6	0.3	0.5	1.7	36.7	4.6	−22.1	40.0	3.5	2
HF-45	4.0	1.1	0.9	1.0	1.0	18.9	7.1	−41.8	27.5	7	1
HF-46	4.0	1.1	0.8	1.0	1.0	19.1	7.1	−35.8	27.5	4	1
HF-47	4.2	1.1	0.9	0.9	0.9	19.8	7.1	−29.8	31.1	3	1
HF-48	4.1	1.2	1.3	2.2	7.1	8.3	8.3	−21.5	33.0	2.5	2
HF-49	4.2	1.2	1.3	2.1	13.1	8.7	8.3	−16.1	33.0	3.5	1
HF-50	4.1	1.2	2.5	4.4	13.8	4.2	8.4	−16.0	33.0	5	3
HF-51	4.3	1.1	4.3	4.3	16.2	4.3	7.8	−13.4	31.7	5	2
HF-52	4.2	1.1	4.2	4.3	21.3	4.2	7.8	−10.9	30.3	6	2
HF-53	4.3	1.2	4.6	4.6	34.1	4.0	7.8	−7.4	34.7	6.5	2
HF-54	4.3	1.1	4.2	4.3	42.7	4.3	7.8	−4.9	30.5	7	3
HF-55	4.2	1.8	2.1	3.8	13.8	4.8	10.0	−20.2	31.0	4	2
HF-56	4.1	1.8	4.0	4.5	4.5	4.1	10.1	−49.0	12.8	7	1
HF-57	4.1	1.8	4.1	4.4	4.4	4.1	10.1	−43.0	14.0	7	1
HF-58	4.2	1.9	4.3	4.4	4.4	4.1	10.1	−37.0	17.1	6.5	1
HF-59	4.4	2.2	4.9	4.7	3.7	3.9	10.1	−33.5	22.9	3.5	1
HF-60	3.9	1.8	4.0	4.8	3.9	3.9	10.1	−31.0	10.7	3.5	1
HF-61	4.1	2.1	4.4	4.8	5.4	3.8	10.1	−29.0	16.2	3.5	1
HF-62	4.1	2.0	2.3	4.5	6.0	4.1	10.1	−28.1	31.0	3.5	1
HF-63	4.1	2.0	2.4	4.5	9.0	4.1	10.1	−24.5	31.0	3	1.5

(*continued on next page*)

Table 5 (*continued*)

No.	ω_{sp} (rad/s)	ξ_{sp}	CAP ($g^{-2}\cdot s^{-1}$)	$T_{\theta 2}$ (s)	K_q ((°)/s)	n_z/α (g/rad)	$\omega_{BW\theta}$ (rad/s)	M_θ (dB)	τ_p (ms)	CHR	PIOR
HF-64	4.1	2.0	2.4	4.5	9.0	4.1	10.1	−24.5	31.0	3	1.5
HF-65	4.2	2.0	2.3	4.2	15.5	4.4	10.1	−20.1	31.0	3	1.5
HF-66	4.0	2.0	4.2	4.8	22.7	3.9	10.1	−16.2	14.3	5.5	1.5
HF-67	3.8	2.3	4.9	6.1	30.6	3.0	10.1	−14.1	14.9	5.5	1.5
HF-68	4.0	1.9	4.1	4.7	4.7	3.9	10.1	−9.0	12.7	6.5	2
HF-69	5.0	1.2	0.9	0.7	0.7	27.8	8.2	−44.4	22.9	7	1
HF-70	5.2	1.1	0.9	0.6	0.6	29.7	8.2	−38.3	25.1	4	1
HF-71	5.2	1.2	0.9	0.6	0.6	28.6	8.2	−34.8	27.7	3.5	1
HF-72	5.6	1.1	1.0	0.6	0.6	31.5	8.2	−28.8	33.1	3	1
HF-73	5.7	0.4	0.8	0.6	5.5	30.6	6.5	−13.7	40.0	6	3
HF-74	5.5	0.3	1.0	0.6	5.5	30.3	2.2	−11.8	42.3	6	2
HF-75	5.7	0.3	1.1	0.6	11.2	30.5	2.2	−5.8	50.2	6	1.5
HF-76	5.7	0.3	1.1	0.6	16.9	30.6	2.2	−2.5	50.8	7	2
HF-77	5.6	0.3	1.0	0.6	25.2	30.3	2.2	1.3	46.2	7	2
HF-78	5.6	0.3	1.0	0.6	35.8	30.4	2.2	4.3	47.4	7	2
HF-79	5.7	1.0	0.7	0.6	5.8	30.6	8.8	−24.1	34.0	2.5	1
HF-80	5.6	1.5	0.6	0.6	5.6	30.6	9.4	−28.0	32.0	2	1
HF-81	6.1	1.1	6.2	3.0	3.1	6.1	12.6	−35.7	8.1	3.5	1.5
HF-82	7.4	0.9	6.6	2.2	6.5	8.3	12.9	−29.3	12.6	3.5	2
HF-83	7.7	0.9	6.0	1.9	23.3	9.7	13.7	−18.6	7.6	5.5	2.5
HF-84	8.5	0.6	1.3	0.6	8.0	30.6	8.9	−20.8	35.0	3.5	1.5
HF-85	8.3	0.9	6.2	1.7	6.3	11.1	14.4	−31.1	9.2	3.5	1

Table 6 Lateral pilot ratings and parameters in MAHT task.

No.	T_r (s)	CHR	PIOR	No.	T_r (s)	CHR	PIOR
HF-86	1.966	8	5	HF-94	0.243	3.5	1.5
HF-87	1.311	7.5	5	HF-95	0.193	3	1.5
HF-88	1.172	7.5	4.5	HF-96	0.122	3	1.5
HF-89	0.982	6.5	4	HF-97	0.088	2.5	1.5
HF-90	0.664	5.5	4	HF-98	0.063	4	2.5
HF-91	0.478	5.5	4	HF-99	0.046	4	2.5
HF-92	0.315	5	3	HF-100	0.030	4	3
HF-93	0.284	4.5	2.5	HF-101	0.018	5.5	4

craft must capture a target as soon as possible and rapidly regulate against disturbance by aggressive maneuvers. The maneuver amplitude of a short-range air combat mission with an attitude change amplitude of approximately 50° is larger than those of small-amplitude maneuvers, which are emphasized by the conventional flying qualities criterion and have an attitude change amplitude of approximately 5°.[24] Thus, a short-range air combat mission requires a higher response rapidity and a greater allowable minimum value of ω_{sp}.

The CAP can be used to reflect the coordination between the initial and steady-state responses. The comparison between the mission-oriented flying qualities evaluation results and the CAP criterion for Category A flight phases and Class IV aircraft is shown in Fig. 6.

For the configurations evaluated in this paper, it can be observed that the CTAT task requires a CAP greater than 0.6 $g^{-2}\cdot s^{-1}$, and the MAHT task requires a CAP greater than 0.28 $g^{-2}\cdot s^{-1}$ in Fig. 6. Therefore, for Level 1 flying qualities in a short-range air combat mission, it is required that the CAP be greater than 0.6 $g^{-2}\cdot s^{-1}$. This means that a short-range air combat mission requires a greater minimum CAP than the conventional CAP criterion, which requires the CAP to be larger than 0.28 $g^{-2}\cdot s^{-1}$. The fact that the large-amplitude maneuvers of short-range air combat require more rapid initial responses than those of small-amplitude maneuvers leads to a preference for more sensitive control and a greater CAP. For the same reason, the CTAT task requires a greater CAP than that of the MAHT task.

5.1.2. Requirements for coordination between attitude and path responses

The coordination between the attitude and path responses can be reflected by $\omega_{sp}T_{\theta 2}$. The comparison between the mission-oriented flying qualities evaluation results and the $\omega_{sp}T_{\theta 2}$ vs ξ_{sp} criterion for the Category A flight phases and Class IV aircraft is shown in Fig. 7.

It can be observed that the mission-oriented flying qualities evaluation results are inconsistent with the $\omega_{sp}T_{\theta 2}$ vs ξ_{sp} criterion. The configurations with Level 1 flying qualities in the CTAT task meet the restriction that

$$-1.82\lg\xi_{sp} + \lg(\omega_{sp}T_{\theta 2}) \leqslant \lg 6 \quad (4)$$

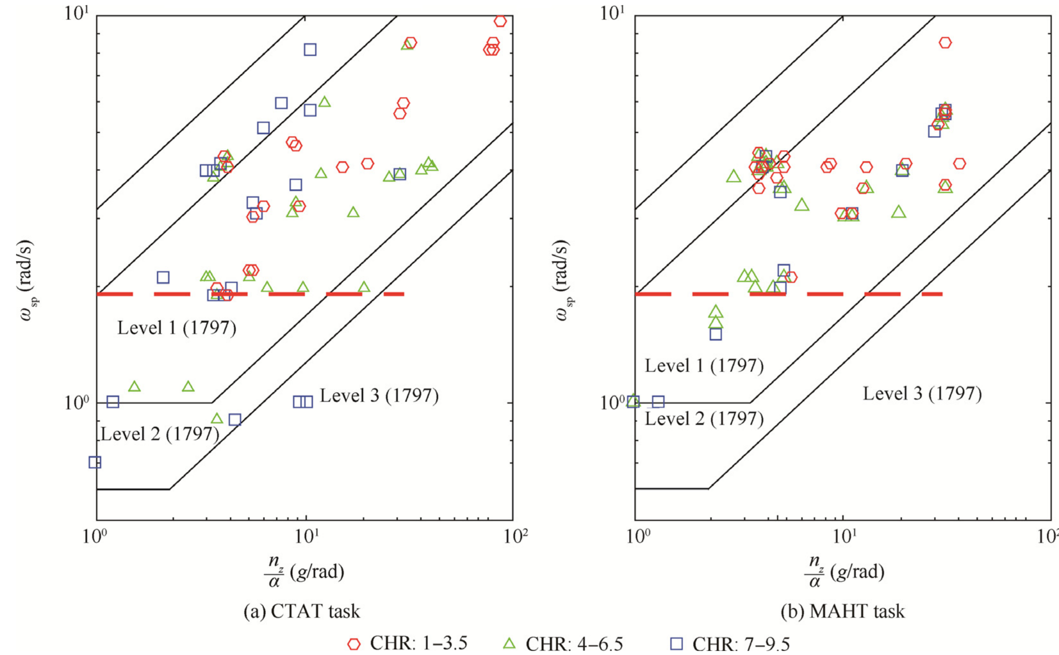


Fig. 5 Results of mission-oriented flying qualities evaluation on ω_{sp} vs n_z/α criterion.

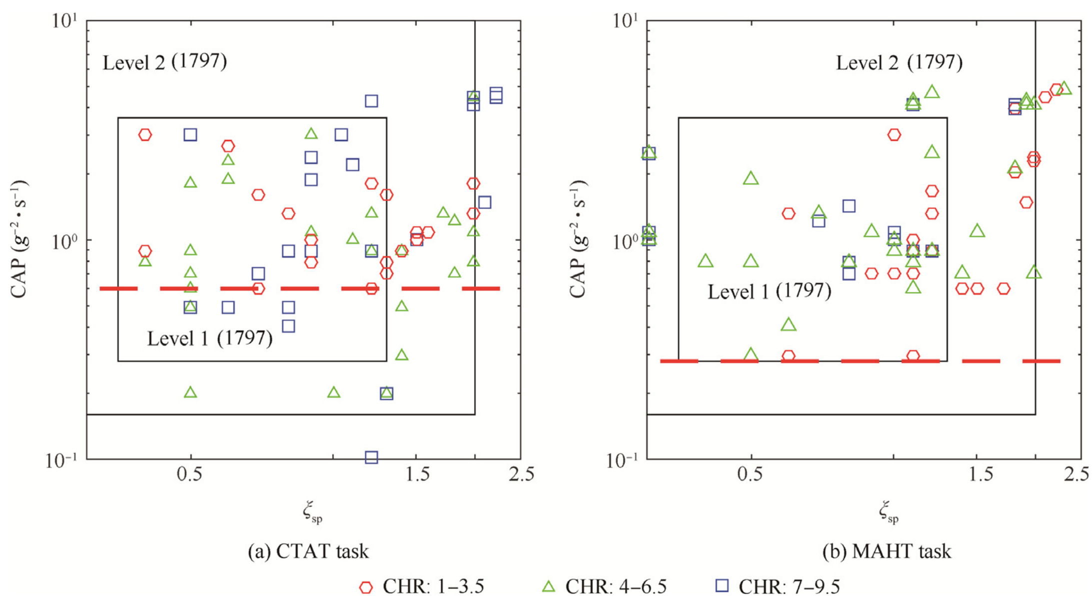


Fig. 6 Results of mission-oriented flying qualities evaluation on equivalent CAP criterion.

and the Level 1 configurations in the MAHT task meet the restriction that

$$-1.82 \lg \xi_{sp} + \lg(\omega_{sp} T_{\theta 2}) \leqslant \lg 11 \quad (5)$$

Therefore, both of the demonstration maneuvers require that a larger $\omega_{sp}T_{\theta 2}$ matches a larger ξ_{sp}, and a smaller $\omega_{sp}T_{\theta 2}$ matches a smaller ξ_{sp}.

This can be attributed to the fact that the $\omega_{sp}T_{\theta 2}$ vs. ξ_{sp} criterion uses $\omega_{sp}T_{\theta 2}$ to reflect the coordination between the attitude and path responses, yet a short-range air combat mission mainly demonstrates the characteristics of attitude control rather than the flight path response. Because a large $\omega_{sp}T_{\theta 2}$ will result in an excessively large pitch rate overshoot,[5] the attitude response predictability requirements of a short-range air combat mission require a large ξ_{sp} to reduce the amplitude of the overshoot and improve the stability. Therefore, a short-range air combat mission requires that a large $\omega_{sp}T_{\theta 2}$ matches the large ξ_{sp}, rather than specific requirements for the coordination between the attitude and path responses.

5.1.3. Requirements for attitude bandwidth

The comparison between the mission-oriented flying qualities evaluation results and the attitude bandwidth criterion for Category A flight phases is shown in Fig. 8.

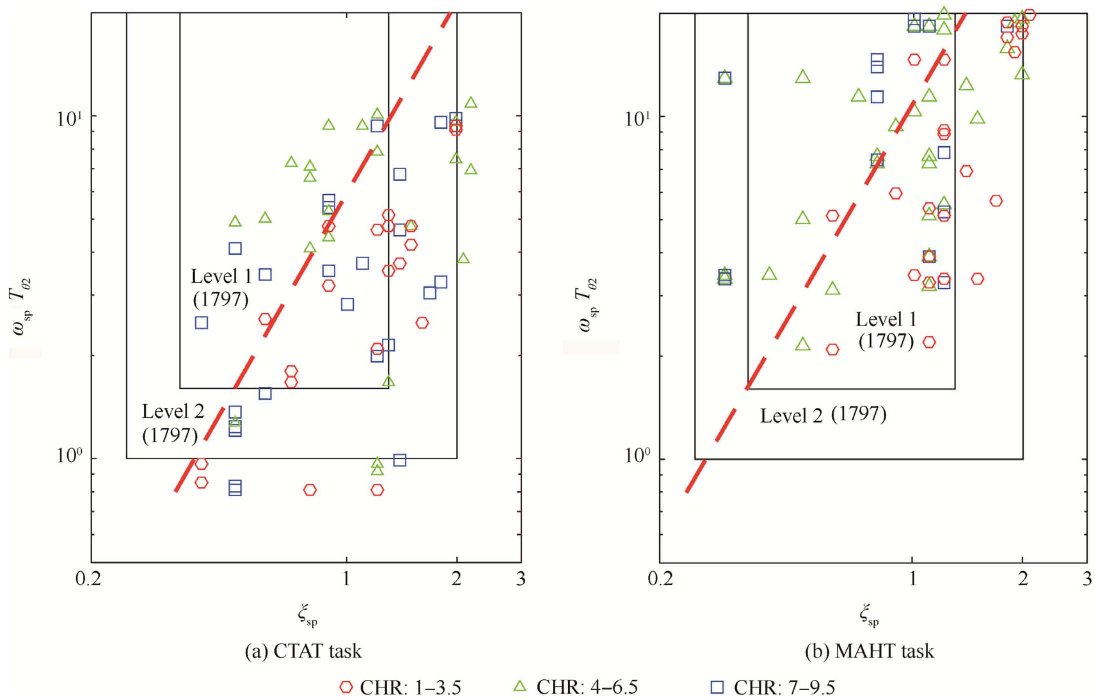


Fig. 7 Results of mission-oriented flying qualities evaluation on $\omega_{sp}T_{\theta 2}$ vs. ξ_{sp} criterion.

The time delay τ_p of all configurations is set at almost the same value, so the conclusions given by this paper have not considered the effect of the time delay, and only the requirement for the attitude bandwidth will be discussed in this section. Fig. 8 shows that the minimum bandwidth for Level 1 in short-range air combat is decreased. Based on the configurations evaluated in this paper, the allowable minimum bandwidth is decreased from 6.5 rad/s to 4.3 rad/s.

The bandwidth criterion for Category A flight phases must consider various maneuvers that belong to Category A flight phases, so the maneuvers that require a bandwidth higher than 6.5 rad/s determine the minimum bandwidth requirement of the bandwidth criterion.[5] However, short-range air combat consists of moderate- and large-amplitude maneuvers, and a pilot can accept a lower response bandwidth as the maneuver amplitude increases.[14] Therefore, the minimum bandwidth requirement of a short-range air combat mission is lower than the bandwidth criterion.

5.2. Flying qualities requirements

From the analysis in the previous sections, it can be observed that the four conventional longitudinal flying qualities criteria cannot accurately reflect the flying qualities requirements of a short-range air combat mission, so new flying quality metrics should be put forward. In short-range air combat, a pilot mainly controls attitudes to accomplish acquisition and tracking, so the attitude bandwidth can reflect the response rapidity and stability requirements of the maneuvers. In addition, it is found from the evaluation experiments that aircraft with different control sensitivity perform different levels of flying qualities. Accordingly, the attitude bandwidth frequency, $\omega_{BW\theta}$, combined with the pitch stick input to attitude transfer function magnitude at the bandwidth frequency, M_θ, will be used to analyze the flying qualities requirements of a short-range air combat mission.

5.2.1. Proposal of flying qualities requirements

The comparison between the mission-oriented flying qualities evaluation results and the combination of $\omega_{BW\theta}$ and M_θ of the test configurations is shown in Fig. 9.

For both the CTAT task and the MAHT task, the configurations with Level 1 flying qualities are concentrated in the Level 1 area which is enclosed with the red dashed lines in Fig. 9. The left boundaries of the Level 1 area are the lower limits on $\omega_{BW\theta}$, the right boundaries are the limits to the combination of $\omega_{BW\theta}$ and M_θ, the upper boundaries are the upper limit on M_θ, and the lower boundaries are the lower limit on M_θ and the combination of $\omega_{BW\theta}$ and M_θ. Based on the CHR, the Level 2 flying qualities area is also determined. It can be observed that the Level 2 boundaries are parallel to the Level 1 boundaries in Fig. 9. In addition, because of the limits of the aircraft flight controller and the aircraft airframe, $\omega_{BW\theta}$ of the test configurations are lower than 15 rad/s. Thus, the black dash-dot-line is used to represent the $\omega_{BW\theta}$ upper boundaries of the test configurations. Fortunately, for a common aircraft, $\omega_{BW\theta}$ has a tendency to be too small and needs a limit of the minimum value.

Although the mission-oriented flying qualities evaluation can reflect the nonlinear characteristics of the test aircraft, the plots of $\omega_{BW\theta}$ and M_θ successfully correlate with the flying qualities levels of the configurations flight tested in a short-range air combat mission. Meanwhile, considering the extensive use of linear parameters in aircraft design, a flying qualities requirement suggestion is put forward based on $\omega_{BW\theta}$ and M_θ. For the given configurations, the Level 1 and Level 2 requirements are suggested in Table 7.

5.2.2. Analysis of flying qualities requirements

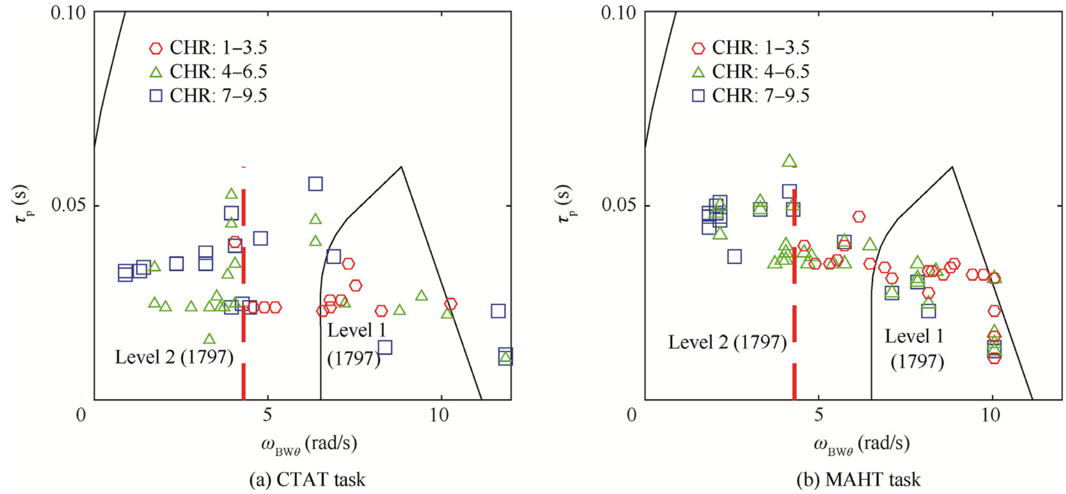


Fig. 8 Results of mission-oriented flying qualities evaluation on the bandwidth criterion.

(1) Attitude bandwidth requirement

In Table 7, it can be observed that both maneuvers require an attitude bandwidth greater than the minimum allowable values to guarantee suitable flying qualities. As a combination of the two maneuver requirements, a short-range air combat mission requires that $\omega_{BW\theta}$ shall not be too small. For the given configurations, $\omega_{BW\theta}$ is required to be greater than 4.5 rad/s to produce Level 1 flying qualities, and 2.1 rad/s to produce Level 2 flying qualities. This can be attributed to the fact that a low bandwidth will increase the acquisition time and reduce the tracking stability. Hence, an excessively low $\omega_{BW\theta}$ will degrade the flying qualities level in a short-range air combat mission.

For example, in the CTAT task, configuration CF-35, whose bandwidth is smaller than the Level 1 requirements, receives pilot comments of a slow initial response. In the MAHT task, configurations HF-18 and HF-25, which cannot meet the Level 1 bandwidth requirements, are also noted to have a too slow initial response and undesirable motions induced by aggressive control. Therefore, if the attitude bandwidth is too low, the task performance and the flying qualities level will be degraded.

(2) Magnitude at bandwidth frequency requirements

The magnitude requirement of a short range air combat mission is the intersection of the requirements of the two demonstration maneuvers that the magnitude at the bandwidth frequency, M_θ, shall not be excessive or too low. For the given configurations, a short-range air combat mission requires M_θ to be between -27 dB and -16 dB to guarantee Level 1 flying qualities, while between -34 dB and -5 dB to guarantee Level 2 flying qualities.

To analyze the magnitude requirement, physical implications of M_θ will be considered firstly. For an aircraft-pilot system consisting of an aircraft with M_θ and an idealized pilot supplying only gain, the crossover frequency will be $\omega_{BW\theta}$ if the gain of the pilot control is $-M_\theta$. The phase margin of the aircraft-pilot system will then be 45°, or the gain margin will decrease to 6 dB. Furthermore, considering the control delay and the fluctuation of the pilot gain, the stability margin will be decreased further, inducing instability of the aircraft-pilot system.[25] Therefore, as an estimate of the highest allowable control gain in short-range air combat, M_θ can represent the requirements for the attitude response magnitude to guarantee the aircraft-pilot system stability. However, aggressive control requires a high pilot gain, which will increase the closed-loop gain of the aircraft-pilot system. Therefore, a short-range air combat mission restricts the maximum value of M_θ to reflect the aircraft-pilot system stability requirements for the amplitude-frequency characteristics. In addition, M_θ is the control sensitivity metric. If M_θ is too low, the pilot will need to give large amplitude control to a small error. Then, the task performance and the flying qualities level will be degraded.

From the comparison between the results of the two demonstration maneuvers, it can be observed that there are different magnitude requirements between them. The CTAT task requires M_θ between -27 dB and -14 dB to guarantee Level 1 flying qualities, while the MAHT task requires M_θ between -36 dB and -16 dB to guarantee Level 1 flying qualities. This difference can be attributed to the frequent and abrupt command changes in the MAHT task. To track the attitude commands precisely, the pilot must control the aircraft more aggressively than in the CTAT task. Therefore, to guarantee the stability of the aircraft-pilot system, the maximum M_θ requirement of the MAHT task is lower than that of the CTAT task. Similarly, more aggressive control and less violent maneuver in the MAHT task allow lower control sensitivity. Thus, the minimum M_θ requirement of the MAHT task is also lower than that of the CTAT task.

(3) Bandwidth and magnitude combination requirement

In both demonstration maneuvers, the combination of $\omega_{BW\theta}$ and M_θ is restricted to the left and right boundaries of the flying qualities Level 1 region. Therefore, a short-range air combat mission requires that $M_\theta + 40\lg\omega_{BW\theta}$ shall be neither too large nor too small. For the given configurations, $M_\theta + 40\lg\omega_{BW\theta}$ shall be lower than 20 dB and higher than 5 dB to guarantee Level 1 flying qualities, and between 1 dB and 24 dB to guarantee Level 2 flying qualities.

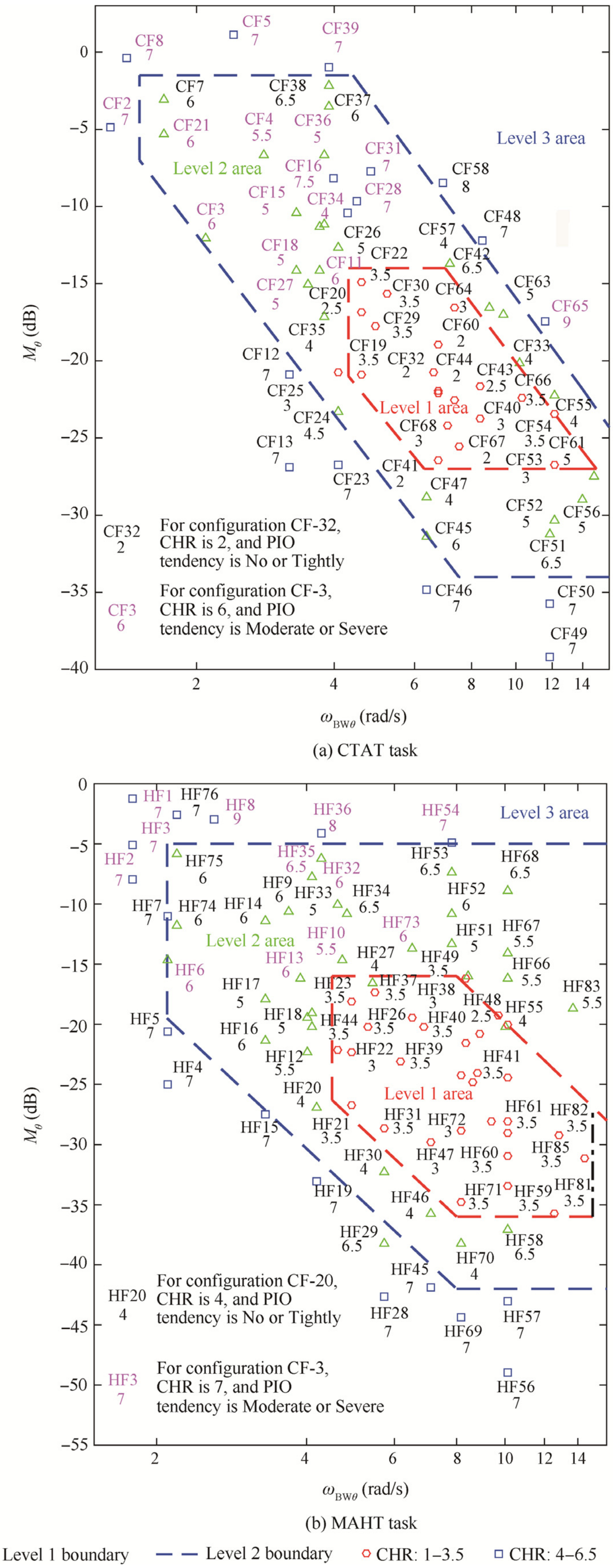


Fig. 9 Pitch attitude bandwidth and control sensitivity of test aircraft mission-oriented flying qualities evaluation.

Table 7 Mission-oriented flying qualities requirements suggestion.

Parameter	$\omega_{BW\theta}$ (rad/s)	M_θ (dB)	$40\lg\omega_{BW\theta}+M_\theta$ (dB)
Level 1 flying qualities requirements of CTAT task	> 4.3	−27 to −14	5–20
Level 2 flying qualities requirements of CTAT task	> 1.7	−34 to −2	1–24
Level 1 flying qualities requirements of MAHT task	> 4.5	−36 to −16	0–20
Level 2 flying qualities requirements of MAHT task	> 2.1	−42 to −5	> −6

The physical implications of $M_\theta+40\lg\omega_{BW\theta}<20$ dB will then be analyzed. For a common aircraft, the equivalent pitch rate transfer function for the pilot input[5] is

$$G(s)=\frac{K_q(s+1/T_{\theta2})}{s(s^2+2\xi_{sp}\omega_{sp}s+\omega_{sp}^2)} \tag{6}$$

To obtain M_θ, s is replaced with $\omega_{BW\theta}$j, and the module value of Eq. (6) is M_θ as

$$M_\theta=20\lg|G(\omega_{BW\theta}\mathrm{j})| \tag{7}$$

where G is the aircraft equivalent pitch rate response transfer function. The expansion of Eq. (7) gives the relation between M_θ, $\omega_{BW\theta}$, and equivalent system gain for the short-period mode K_q as

$$M_\theta=20\lg K_q-40\lg\omega_{BW\theta}-10\lg\frac{(\omega_{sp}^2/\omega_{BW\theta}^2-1)^2+4\xi_{sp}^2\omega_{sp}^2/\omega_{BW\theta}^2}{1+1/T_{\theta2}^2\omega_{BW\theta}^2} \tag{8}$$

The approximate expression of $\omega_{BW\theta}$ can be found in Ref. [26] as

$$\omega_{BW\theta}\approx\omega_{sp}\left(\frac{\pi\xi_{sp}}{4}+\sqrt{\frac{\pi^2\xi_{sp}^2}{16}-\frac{2\xi_{sp}}{\omega_{sp}T_{\theta2}}+1}\right) \tag{9}$$

Let ε be the last term of Eq. (8) as

$$\varepsilon=10\lg\frac{\left(\omega_{sp}^2/\omega_{BW\theta}^2-1\right)^2+4\xi_{sp}^2\omega_{sp}^2/\omega_{BW\theta}^2}{1+1/\left(T_{\theta2}^2\omega_{BW\theta}^2\right)} \tag{10}$$

The range of ε can then be written as

$$\frac{\frac{4}{\left(\pi/4+\sqrt{\pi^2/16+1/\xi}\right)^2}}{1+\frac{16}{\left(\pi\xi\omega_{sp}T_{\theta2}\right)^2}}\leq\varepsilon\leq\left(\frac{16}{\pi^2\xi^2}-1\right)^2+\frac{64}{\pi^2} \tag{11}$$

Based on the value ranges of ξ_{sp} and $\omega_{sp}T_{\theta2}$, the limit to ε can be obtained as

$$-8\leqslant\varepsilon<12 \tag{12}$$

Therefore, the last term of Eq. (8) is bounded. If ε is ignored, the relations between the equivalent system gain for the short-period mode K_q, attitude bandwidth frequency $\omega_{BW\theta}$, and attitude response magnitude at the bandwidth frequency M_θ will be approximated as

$$20\lg K_q\approx M_\theta+40\lg\omega_{BW\theta} \tag{13}$$

By comparing Eq. (13) with the requirement for $M_\theta+40\lg\omega_{BW\theta}$ in Table 7, it can be found that the physical implication of the Level 1 requirement is that K_q of the aircraft shall be between 5 dB and 20 dB, and the physical implication of the Level 2 requirement is that K_q of the aircraft shall be between 1 dB and 24 dB. To check this conclusion, K_q of the configurations near the Level 1 area right boundary of the CTAT task are shown in Table 8.

It can be observed that K_q of the configurations near the Level 1 area right boundary are approximately 20 dB, so it can be verified that the requirement for $M_\theta+40\lg\omega_{BW\theta}<20$ dB is a restriction on K_q.

K_q is related to the attitude response magnitude, especially the pitch acceleration response magnitude. In a short-range air combat mission, both acquisition and fine tracking require response predictability. Therefore, if K_q is too large, the initial response will be abrupt, and the steady-state response will be unpredictable. If K_q is too small, the initial response will be sluggish, and the control sensitivity will be too low. These characteristics will result in a poor tracking accuracy and degrade the flying qualities. Accordingly, a short-range air combat mission requires that K_q shall be neither too large nor too small.

6. Lateral flying qualities requirements

An analysis of the lateral flying qualities requirements is conducted by a method similar to that for the longitudinal axis. The comparison between the mission-oriented flying quality evaluation results and the roll mode time constant of the test configurations is show in Fig. 10.

In Fig. 10, it can be observed that both maneuvers require that the roll mode time constant shall be in appropriate ranges to guarantee Level 1 flying qualities, which are narrower than that allowed by the conventional flying qualities criteria. Based on the configurations tested in this paper, the CTAT task requires T_r to be in the range of 0.13–0.18 s, and the MAHT task requires T_r in the range of 0.08–0.26 s. For the Level 2 flying qualities, the maximum T_r shall be lower than 0.8 s in the CTAT task and 1 s in the MAHT task. However, similar to $\omega_{BW\theta}$, the Level 2 flying qualities requirements to the minimum T_r cannot be found because of the limits of the test aircraft. Also fortunately, for a common aircraft, T_r has a tendency to be too large and needs a limit of the maximum value.

Compared with the MAHT task, the CTAT task requires T_r to be in a narrower range. There are two reasons for the higher requirements. Firstly, in the CTAT task, the lateral tracking error is presented as a lateral distance between the reticle and the target. To accomplish lateral acquisition and tracking, a pilot need to control the roll attitude to move the reticle laterally. However, in the MAHT task, the pilot controls the roll attitude to directly track the attitude command. Therefore, the task difficulty of the CTAT task is greater than that of the MAHT task, and the CTAT task has stricter requirements for T_r. Secondly, in the CTAT task, to maintain the target within the reticle, the pilot must conduct longitudi-

Table 8 Configurations near right boundary of CTAT Task.

Configuration	CF-33	CF-42	CF-54	CF-55	CF-56	CF-57	CF-63
K_q (dB)	23.4	22.9	22.6	24.2	22.5	19.1	19.2

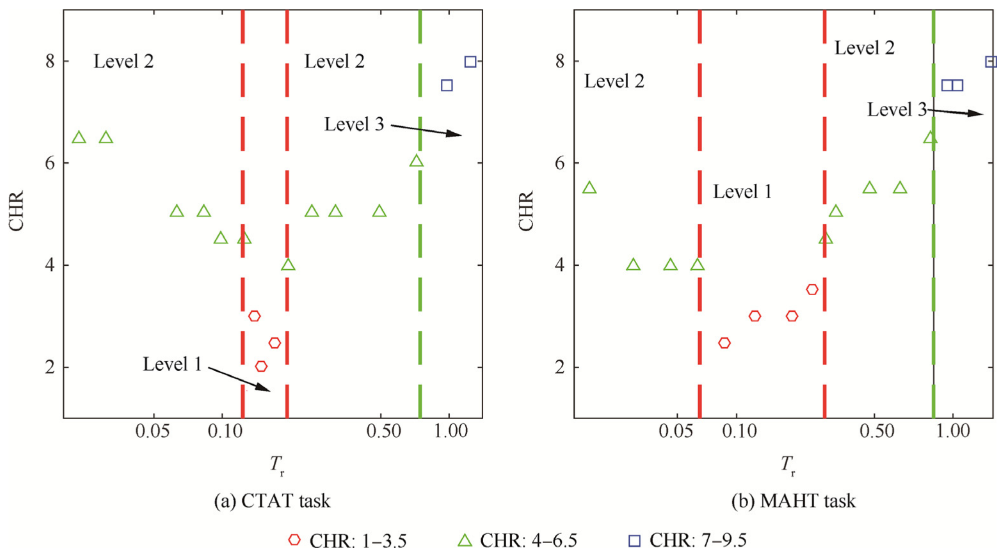


Fig. 10 Roll mode time constant of test aircraft for mission-oriented flying qualities evaluation.

nal and lateral acquisition and tracking simultaneously. However, in the MAHT task, the pilot can track the pitch and roll attitudes independently. Therefore, the low longitudinal and lateral coupling in the MAHT task relaxes the requirements for T_r.

Meanwhile, the requirements of a short-range air combat mission can be obtained from the intersection of the requirements of the two demonstration maneuvers. For the given configurations, a short-range air combat mission requires T_r to be within the range of 0.13–0.18 s to guarantee Level 1 flying qualities and be lower than 0.8 s to guarantee Level 2 flying qualities. In a short-range air combat mission, roll-axis maneuvers are not only used to change the direction of the lift vector to enter the maneuver plane as in conventional maneuvers, but also conducted by aggressive and precise pilot control to capture and track a target. Accordingly, a short-range air combat mission has higher requirements for T_r than the conventional flying quality criteria. Specifically, to meet the requirements of roll response rapidity, T_r shall not be too large. However, because of the first-order response characteristics of the roll response, it is difficult to predict the steady-state response. To prevent an abrupt initial response from further deteriorating the predictability, T_r shall not be too small.

7. Conclusions

The flying qualities requirement suggestions of a short-range air combat mission are revealed as complements to the existing flying qualities requirements. The suggestions are preliminary opinions and need to be further validated by flight tests and practice. It should be noted that modern air combat is systemic confrontation involving aircraft, airborne weapons, airborne radar, air intelligence support, and so on. Therefore, the flying qualities level of a fighter is one of the factors affecting the combat result. A fighter that meets the flying qualities requirement suggestions can improve the response speed and stability of the aircraft-pilot system. When the properties of weapons, situational awareness ability, and support forces are similar, a fighter with more appropriate flying qualities can achieve a desired situation in short-range air combat.

(1) The bandwidth criterion, equivalent CAP criterion, ω_{sp}-$T_{\theta 2}$ vs ξ_{sp} criterion, or ω_{sp} vs $n_z\alpha$ criterion cannot reflect the flying qualities requirements of a short-range air combat mission exactly. Based on the mission-oriented flying qualities evaluation, the differences between the four commonly used flying qualities criteria and the flying qualities requirements of a short-range air combat mission are obtained. Compared with the conventional flying qualities criteria, a short-range air combat mission requires a higher ω_{sp} and a larger CAP, allows a lower $\omega_{BW\theta}$, a larger ξ_{sp}, and a lower $\omega_{sp}T_{\theta 2}$, and demands that a larger $\omega_{sp}T_{\theta 2}$ matches a larger ξ_{sp}. For the configurations tested in this paper, a short-range air combat mission requires ω_{sp} higher than 2 rad/s, the CAP greater than 0.6 $g^{-2}s^{-1}$, and $\omega_{BW\theta}$ higher than 4.3 rad/s to guarantee Level 1 flying qualities.

(2) Based on the mission-oriented flying qualities evaluation, a new metric to define the longitudinal flying qualities requirements of a short-range air combat mission is put forward. A combination of the pitch attitude bandwidth $\omega_{BW\theta}$ and the pitch attitude response magnitude at the bandwidth M_θ can reflect the flying qualities require-

ments of a short-range air combat mission comprehensively. Based on the evaluation results of the configurations tested in this paper, it is suggested to guarantee Level 1 flying qualities in a short-range air combat mission that $\omega_{\mathrm{BW}\theta}$ shall be higher than 4.5 rad/s, M_θ shall be within the range of $-27\,\mathrm{dB}$ to $-16\,\mathrm{dB}$, and $M_\theta + 40\lg\omega_{\mathrm{BW}\theta}$ shall be within the range of 5 dB to 20 dB. Meanwhile, to guarantee Level 2 flying qualities in a short-range air combat mission, it is suggested that $\omega_{\mathrm{BW}\theta}$ shall be higher than 2.1 rad/s, M_θ shall be within the range of -34 dB to -5 dB, and $M_\theta + 40\lg\omega_{\mathrm{BW}\theta}$ shall be within the range of 1 dB to 24 dB.

(3) To guarantee Level 1 flying qualities in a short-range air combat mission, the roll mode time constant T_r is suggested to be within the range of 0.13–0.18 s based on the mission-oriented flying qualities evaluation results. Meanwhile, to guarantee Level 2 flying qualities, T_r is suggested to be lower than 0.8 s, which is narrower than the range allowed by the conventional flying qualities criteria.

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