A Limited Evaluation of a Model-Free Control Law System

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This paper presents the flight test results and lessons learned of a limited evaluation of a longitudinal model-free adaptive control law system which had not been flown on a piloted aircraft; executed by USAF TPS Class 21B in March 2022. The control law under test was integrated onto the Calspan VSS Learjet which is able reproduce the dynamics of a wide variety of aircraft while remaining also providing a safety sandbox for new control systems to operate. The limited evaluation quantitatively measured the ability of the control law to produce the desired dynamics and also evaluated multiple single-ship and formation handling qualities tasks to qualitatively evaluate the new control law. The control law demonstrated an ability to produce the specified short period dynamics with a wide variety of underlying dynamics but also added a a large equivalent time delay which negatively impacted the fine tracking of the controller. This testing demonstrates the unique challenge of model following controls in that the objective is not to evaluate what the flying and handling qualities are, but how closely they match the desired dynamics. Overall, this test program highlighted the benefit of flight control testbed aircraft which can greatly reduce the technical and safety risk of developmental flight control systems, to include autonomous systems.

I. Introduction

Legacy flight control systems have typically been designed utilizing a robust math model which was complex, expensive, and laborious to test and fine-tune. Adaptive control laws utilize a simplified model, detect the differences between actual dynamics and the model, and then modify the flight control inputs to account for those differences. This limits the complexity of the aircraft model and may reduce the amount of time to design the flight control algorithms.

One area of adaptive controllers is model reference adaptive controllers (MRACs). The design goal of MRACs is to develop an adaptive controller which causes the aircraft to respond based on some defined model.[1] This model would, ideally, have known good flying qualities for the mission of the aircraft. A challenge of testing these controllers is often identifying the root cause of abnormal behavior: either the model, the adaptive controller, or the integration between the two.

A Gaussian Process MRAC which utilized a Bayesian scaling factor to quantify the confidence in the adaptive model was flight tested utilizing quad-copters in a controlled environment. The testing utilized both predefined flight path tracking tasks in addition to a psuedo-random sum of sines tracking task.[2]

Another control design implmented a Kalman filter observer to estimate velocity parameters in order to alleviate undesirable oscillations which were hypothesized to be the result of a observed noise in the airspeed sensor. Flight testing consisted of simple flight path and airspeed captures but were performed with simulated surface failures in order to stress the system. Results showed the control design with the filter performed better in both nominal testing and testing with surface failures.[3]

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Although MRAC's have the ability to adapt to differing configurations and flight conditions, they are typically limited to flying on a similar performing aircraft. Model-free controllers have the advantage of not requiring an underlying dynamics model, only a desired model. Theoretically, the controller could be integrated onto any aircraft and produce the same flying and handling qualities.

This paper presents the flight test strategy and results of a pitch-axis Model-Free Sliding Mode Controller integrated on the Calspan Variable Stability System (VSS) Learjet. This paper first presents a brief background of the controller and the Calspan VSS Learjet. Next, the flight test results are presented. Finally, a summary of the lessons learned are presented.

II. Model Free Sliding Mode Controller

The system under test was a model-free, sliding-mode control law (MFSMC) designed by students and faculty members at Rochester Institute of technology (RIT). The MFSMC may provide aircraft designers the flexibility to rapidly integrate the new control law into a variety of systems while only needing to choose a single set of desired dynamics. This would render the control law not only highly adaptive, but extremely versatile as a solution for future manned aircraft controls, as well as autonomous aircraft and vehicles. [4][5]

The MFSMC assumes a set of desired dynamics to include state and control gain then drives the actual dynamics of the system towards the desired dynamics. It does this without knowledge of the actual aircraft dynamics. Instead, the system solely relies on state and control measurements. The MFSMC then utilizes the error between the desired and actual dynamics to calculate the appropriate control inputs. While designing the controller, Lyapunov's stability criterion is used to ensure closed-loop asymptotic stability. [5]

The desired dynamics were assumed to be of the form in Eqn. (1) where q is pitch rate and u is the elevator control input. The variables A and B are constants.

$$\dot{q} = Aq + Bu \tag{1}$$

Figure 1 presents a notional example of the desired behavior of a pitch axis MFSMC. In this example it is assumed u is fixed for the desired dynamics. The underlying dynamics of the aircraft will begin at an arbitrary state depicted by the black dot. The MFSMC calculates inputs based on the pilot inputs and desired state in order to drive the actual dynamics towards and along the desired dynamics (also known as the sliding surface). A boundary layer is used within the MFSMC to control the rate at which the actual dynamics approach the desired dynamics to prevent undesired oscillations.

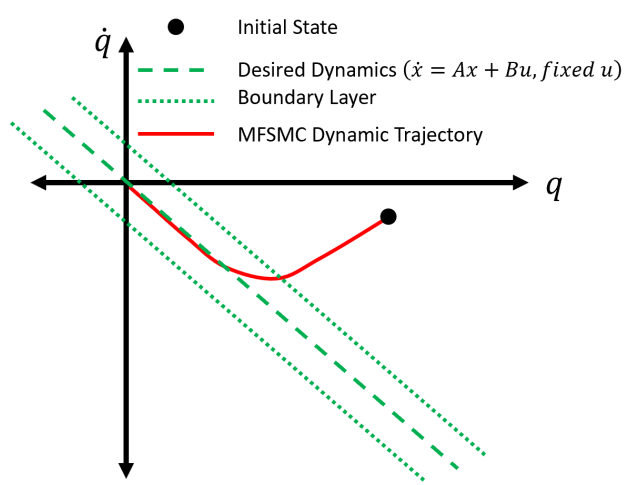

Fig. 1 Notional MFSMC Example, Fixed u

In this test, the MFSMC was implemented in the aircraft pitch axis assuming linear desired dynamics. A simplified functional diagram of the controller is presented in Fig. 2. A challenge of this implementation was state data requirements of the MFSMC. The MFSMC requires state measurements in order to accurately identify the error between the actual

and desired dynamics. In this implementation, the required measurements were pitch rate, pitch acceleration, and control surface deflection. Pitch rate and control surface deflection are common measurements however pitch acceleration is less common.

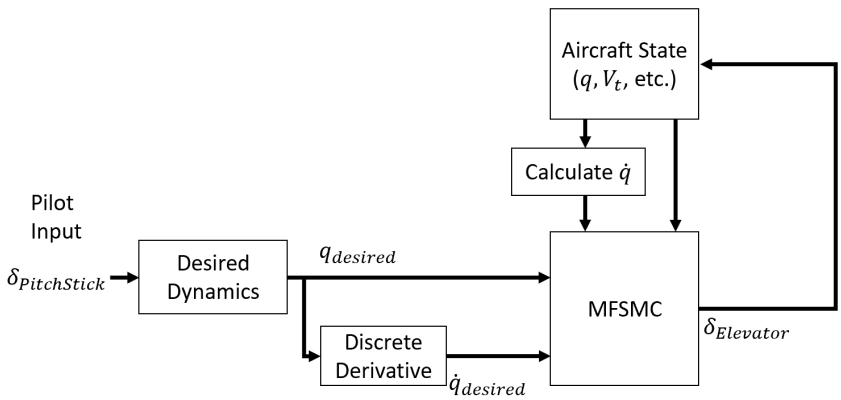

Fig. 2 Functional MFSMC Block Diagram

Pitch acceleration can be a noisy parameter so the test team and system designers allowed for multiple sources which could be tested at the beginning of the test campaign to determine the best source for the remaining testing. The six pitch acceleration sources were:

1) Discrete derivative of pitch rate
2) Sliding mode differentiator from pitch rate
3) Discrete derivative of pitch rate with $20\frac{rad}{s}$ lag filter
4) Estimation from accelerometer and rate signals
5) Finite differentiation with Muller filter
6) INS pitch acceleration

III. Calspan Variable Stability System Learjet

The test team utilized the Calspan VSS Learjet, Fig. 3, which acts as a flight control and unmanned system test bed. The VSS is a four degree of freedom in flight simulator. The VSS is able to simulate the dynamics of a wide variety of aircraft and control the LJ-25 to replicate the simulated dynamics in-flight. These dynamics may simply replicate the bare airframe dynamics of different aircraft or may also include the effects of experimental control laws.

Fig. 3 LJ-25D Variable Stability System

The VSS has a complex safety system which allows a variety of dynamics, to include unstable systems, to be simulated. The heart of the safety system is the cockpit layout. An evaluator pilot sits in the right seat and provides

control inputs to the VSS simulation. The evaluator pilot may use a center or side stick depending on the simulation but the controls are not directly connected to the control surfaces. A safety pilot is always present in the left seat with production representative controls directly connected to the control surfaces.

The VSS contains a set of safety logic which automatically disengages the control law under test if an unsafe situation develops. This set of safety logic includes basic flight parameters like load factor, angle of attack and airspeed in addition to subsystem parameters like surface rates and VSS health monitors. Additionally, the safety pilot may manually disengage the VSS at any time. Control of the aircraft is immediately returned to the safety pilot upon disengagement. The safety system allows for any manner of dynamics and control laws to safely be tested with the knowledge that unsafe situations are prevented from developing due to the proven safety system. The VSS has been operated by Calspan for decades and has proven to be an effective and safe system.

IV. Flight Testing

The MFSMC underwent flying and handling qualities testing to determine if the control law could recover the desired flight dynamics and what, if any, impact the MFSMC had on the aircraft handling qualities as perceived by the pilot. Testing was performed at 250 KCAS and 15,000 ft PA which is the heart of the LJ-25D VSS flight envelope. The tested MFSMC was only active in the pitch axis.

The flying qualities testing utilized pitch frequency sweeps to generate response data which underwent curve fitting in the frequency domain to determine the equivalent system dynamics; also known as the Low Order Equivalent System (LOES) Method. The low order equivalent system method is a curve fit of test frequency response data utilizing an assumed transfer function. This method allows the major parameters of a system to be calculated, such as short period natural frequency, without attempting to match any higher order dynamics. The method was followed for the aircraft pitch-axis according to [6]. Frequency sweeps were performed both with the MFSMC enabled and disabled. This allows the team to characterize how much the MFSMC altered the aircraft dynamics

The handling qualities testing was conducted in a buildup approach beginning with single ship multi-function display tracking tasks and ending with formation tracking tasks with a target aircraft. Handling qualities ratings and pilot comments were collected during all tracking tasks with the control law on and off for comparison. This paper will focus on the formation tracking task results.

A. Baseline Configurations

Four dynamically different aircraft configurations were selected to stress the MFSMC across a range of dynamics from benign to unstable. The configurations varied from level 1 to level 3 flying qualities (according to the CAP criterion [6]) as well as a statically unstable configuration.

The short period characteristics of the baseline configurations were determined via a LOES curve fit of flight test frequency sweep data. Equation (2) was used as the equivalent system for the analysis. [6] The variable K is the overall system gain while τ is the equivalent time delay.

$$\frac{q_{desired}}{\delta_s} = K \frac{s + \frac{1}{\theta_2}}{s^2 + 2\zeta\omega_n + \omega_n^2} e^{-\tau s} \tag{2}$$

Figure 4 presents the flight test data and LOES fit for baseline (i.e., MFSMC Off) configurations A, B, and C . Configuration D was not presented as the statically unstable configuration did not produce adequate frequency response with the control law disengaged. All flight test data points used in the LOES fit and presented in Fig. 4 had a coherence greater than 0.5. Qualitatively, a good fit was achieved for the presented configurations.

The baseline configurations are summarized in Table 1 along with their flight test short period characteristics. The parameters show breadth of dynamics systems selected for this test. Additionally, it can also be seen that the combined VSS and MFSMC system do have some time delay, approximately 0.07-0.10s.

B. Desired Dynamics

The desired dynamics were chosen to be similar to Configuration A by the system designers. Selecting a configuration similar to one of the underlying configurations allows the team to ensure the controller does not negatively impact the desired dynamics in this nominal scenario. As noted early in this paper, the tested version of the MFSMC was only active in the pitch axis.The design of the MFSMC utilized Eqn. (3) as the reference for the desired dynamics. The low-pass filter, $5/(s+5)$, was added by the designers as a result of excessive noise seen during the initial simulations.

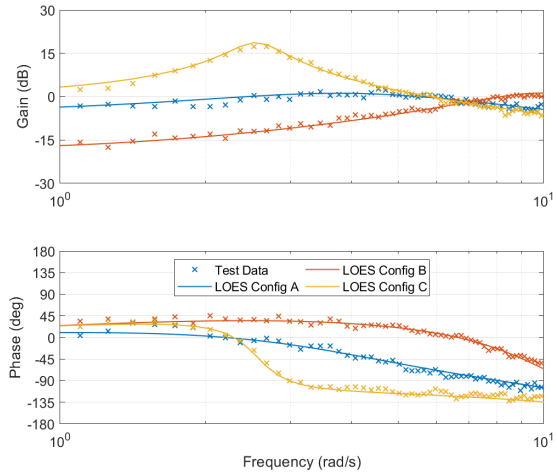

Fig. 4 Baseline Configuration Results

Table 1 VSS Configurations and Short Period Characteristics, MFSMC Off

Configuration	FQ Level	$\omega_n, \frac{rad}{s}$	ζ	K	$T_{\theta_2}(s)$	$\tau(s)$
A	1	4.0	0.70	6	0.69	0.07
B	2	10.0	0.35	8	0.69	0.10
C	3	2.6	0.12	4.6	0.69	0.07
D	Statically Unstable	N/A	N/A	N/A	N/A	N/A

$$\frac{q_{desired}}{\delta_s} = \frac{T_{\theta_2}s + \omega_n^2}{s^2 + 2\zeta\omega_n + \omega_n^2}\frac{5}{s+5} \tag{3}$$

The experimental nature of the control law allowed data to be recorded from a variety of sources within the control law, to include the desired dynamics parameter. This allowed the team to verify exactly what desired dynamics being provided to the control law. A LOES analysis was performed on frequency data from the input to the measured desired dynamics output. The resulting frequency response data and LOES fit are presented in Fig. 5.

Measuring the desired dynamics during a frequency sweep allows any additional dynamics present within VSS to be captured allowing the flight test results to be compared to the actual desired dynamics being provided to the MFSMC. Equation (4) resulted in the best LOES fit utilizing the variables Table 2; the desired values of T_{θ_2}, ω_n, and ζ are provided for comparison. For the interested reader, the gain margin of this transfer function is 4.8 dB and the phase margin is 25 deg. This analysis was performed for all MFSMC enabled frequency sweeps and resulted in the same response.

$$\frac{q_{desired}}{\delta_s} = K\frac{\omega_n^2\left(T_{\theta_2}s + 1\right)}{s^2 + 2\zeta\omega_n + \omega_n^2}\frac{5}{s+5}e^{-\tau s} \tag{4}$$

C. Model Free Sliding Mode Control Performance

The model following performance of the MFSMC was evaluated using a LOES analysis as described in the previous sections. However, the design of the controller drove the idea to perform two separate analyses. The first was a classic LOES analysis utilizing Eqn. (2) to determine how well the controller is predicted to fly. The second was a fit utilizing an expanded model to demonstrate how well the MFSMC could follow the desired dynamics which included an additional lag filter as described in the previous section.

Figure 6 presents a detailed view of the results for configuration C. The black data points are the frequency sweep results with the MFSMC off. The Baseline fit curve utilizes Eqn. (2) as its model and the exact parameters may be

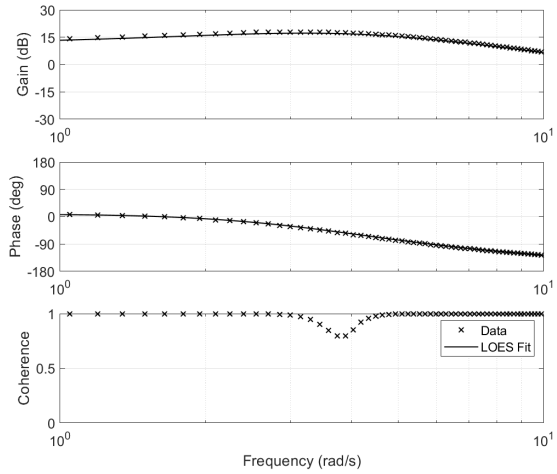

Fig. 5 Flight Test Desired Dynamics

Table 2 Desired Dynamics

Parameter	Desired/Measured
T_{θ_2}	$0.8s$
ω_n	$4.0\frac{rad}{s}$
ζ	0.7
τ	$0s$
K	3.4

found in Table 1. The first observation that is made with the MFSMC on is that it did significantly change the dynamics of the aircraft. However, the LOES fit utilizing Eqn. (2) was not able to capture the higher frequency response as shown by the dashed gold line diverging from the gold data points above approximately $7\frac{rad}{s}$. The difference appeared to be linear indicating additional higher order effects, such as the lag filter in the desired dynamics.

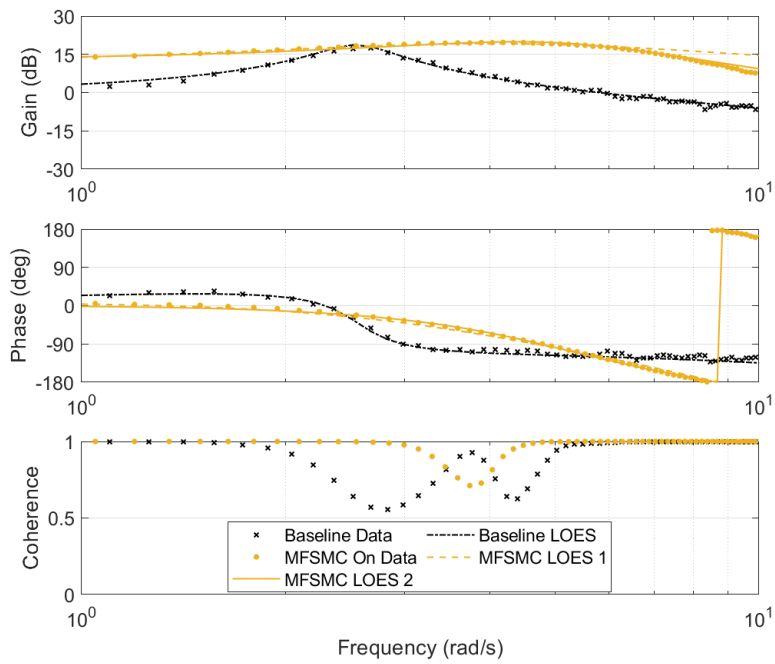

Fig. 6 Configuration C Results Detail

A secondary fit was performed utilizing Eqn. (4), including the lag filter, and resulting in the solid gold fit in Fig. 6. Qualitatively this provided an excellent fit for the entire model. The difference between an Eqn. (2) and an Eqn. (4) fit was seen for each configuration.

The difference in these LOES analyses is that the fit using Eqn. (2) focuses on the overall response of the aircraft as perceived by the pilot. Conversely, the fit using Eqn. (4) acknowledges that the goal of the MFSMC control is to follow the desired dynamics, lag filter included. Table 3 presents the parameter results of the Eqn. (2) fit. The resulting dynamics match the model relatively well except for the excessive time delay. This time delay ended up being the source of many comments in the handling qualities evaluation. The results indicate the MFSMC could follow dynamics well but added excessive time delay. However, it is important to note that the included lag filter will also add perceived time delay.

Table 3 MFSMC Low Order Equivalent System (Eqn. (2))

Configuration	$\omega_n, \frac{rad}{s}$	ζ	K	$T_{\theta_2}(s)$	$\tau(s)$
Design	4.0	0.7	N/A	0.69	0.00
A	3.6	0.69	35	0.8	0.21
B	3.8	0.85	25	0.8	0.17
C	4.2	0.75	55	0.8	0.25
D	3.6	0.69	42	0.8	0.21

Table 4 presents the results of the LOES analysis utilizing Eqn. (4); including the lag filter. These results show that the time delay has been reduced to more tolerable values. Consultation with Calspan experts indicated the typical time delay of the VSS is between 60 ms and 100 ms correlating with these results. However, the equivalent system damping

and natural frequency did not match the measured desired dynamics as well as with the previous analysis.

Table 4 MFSMC Low Order Equivalent System Parameters (Eqn. (4)

Configuration	$\omega_n, \frac{rad}{s}$	ζ	K	$T_{\theta_2}(s)$	$\tau(s)$
Desired Dynamics	4	0.7	3.7	0.8	0
A	4.5	0.52	4	0.5	0.09
B	5	0.72	2.7	0.6	0.06
C	5	0.45	4.5	0.5	0.11
D	4	0.55	4.4	0.65	0.09

Although the parameter values did not match exactly, the overall system behavior was driven towards the desired dynamics. Figure 7 presents a summary of the baseline and MFSMC results along with the LOES analysis using Eqn. (4). The desired dynamics are shown with a black line. Note that the baseline configuration D is not shown as it was statically unstable and did not produce a good frequency response.

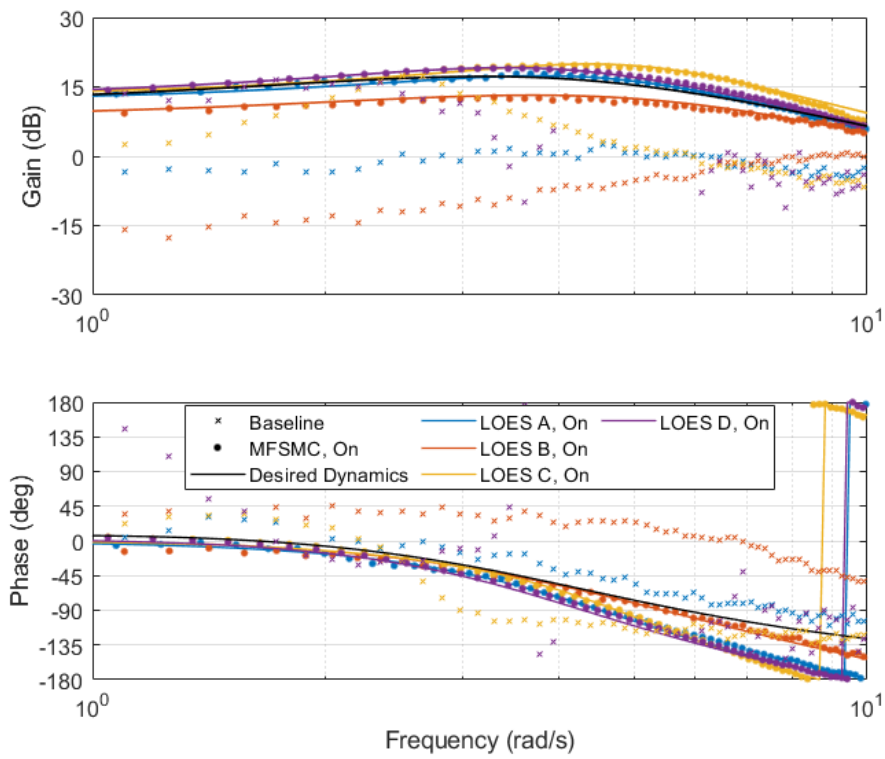

Fig. 7 Frequency Sweep Summary

Figure 7 shows that the MFSMC could adapt to a wide range of aircraft configurations and drive the dynamics towards a desired configuration. Notably, configurations A, C, and even D matched the desired dynamics well in gain but appeared to diverge in phase past $5 fracrads$. Conversely, configuration B matched well in phase while not matching in gain until higher frequencies. No configuration changes were noted in the flight test record or observed in the record which would explain this behavior. It is noted that configuration B had the lowest gain with a higher phase among the baseline configurations. Overall, the MFSMC was able to drive the dynamics of a wide variety of configurations toward a set of desired dynamics. The next section will analyze the resulting handling qualities of these systems.

D. Handling Qualities

The handling qualities assessment consisted of both single ship and formation tracking tasks. All tasks utilized the Cooper-Harper handling qualities rating scale to assess the performance of the aircraft in each task.[7] The single ship task displayed a target on a multi-function display in front of the pilot who maneuvered the test aircraft in the pitch axis to follow the target. The details of these results may be found in the HAVE WHITE CLAW Technical Information Memorandum. [8].

The two evaluator pilots (the project pilots) were students at the United States Air Force Test Pilot School. Pilot A had approximately 1,500 flight hours, primarily in the F-15C Eagle. Pilot B had approximately 3,000 hours, primarily in the KC-10A Extender. Due to the short testing window, both pilots were not able to fly all tasks in all configurations with the MFSMC on and off.

The formation tracking tasks utilized a T-38C Talon as the target aircraft. The tasks built up in difficulty starting with a distant task. The task required the learjet to be flown between 100 ft to 300 ft from the T-38C to the targets left and just aft (30 deg to 60 deg) of a line through the CG of the T-38C and out the left wing. The forward/aft positioning was not a task criteria and was selected to ensure the safety pilot, in the left seat, could see the target aircraft.

The task was to keep the nozzles of the T-38C within a set of tracking criteria which was printed on transparent paper and taped to the aircraft window; the position was recorded to ensure every pilot utilized the same criteria. The target aircraft performed gentle maneuvering of from $0.5g - 1.5g$. Figure 10 presents the desired (solid lines) and adequate (dashed lines) criteria for the distant tracking task. A potential issue with this method was that the tracking performance of the pitch controller could be contaminated by the roll axis of the aircraft which was not being evaluated (e.g., rolling the test aircraft will move the target out of the tracking criteria). The evaluation pilot's were instructed to only evaluate the longitudinal axis and utilize their judgment to determine when the roll-axis was affecting the task.

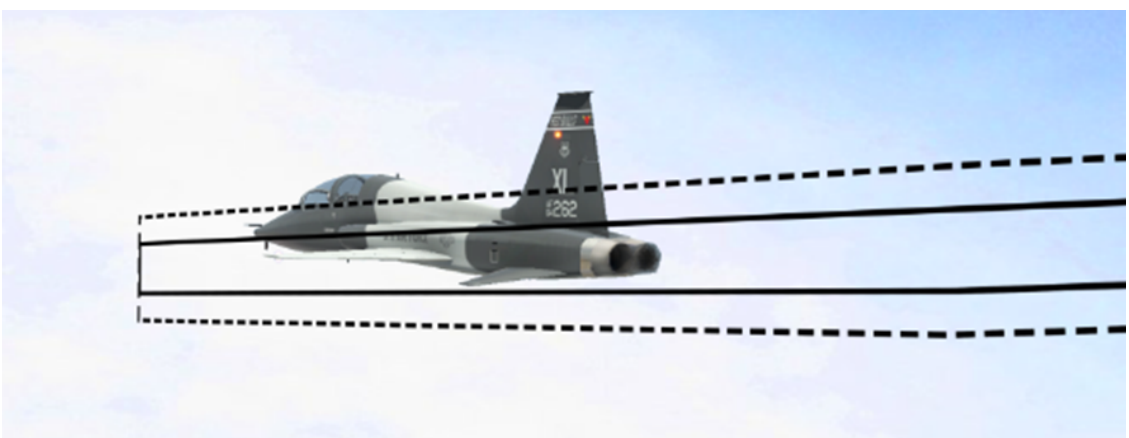

Fig. 8 Desired (solid Lines) and Adequate (dashed lines) Tracking Criteria

The distant tracking task results are presented in Fig. 9. Although the configurations A, B, and C were chosen to recreate level 1, 2, and 3 flying qualities, the handling qualities did not precisely match. Configuration A was a nominal configuration and received level 1 handling qualities ratings. Configuration B had the worst ratings due to its sluggish response that made the task difficult; near-full stick deflections were required to complete the task. Configuration C had observable oscillations but the pilot was able to compensate and complete the task. The unstable configuration was slightly easier to fly than configurations B and C because it was well-damped with a low response rate, despite its static instability, making the instability predictable and allowing the evaluator pilots to complete the task. Overall, the baseline testing demonstrated a wide variety of baseline configurations to stress the MFSMC. Of note, Configuration B with the MFSMC off was poor enough that the tracking close tracking task would not be attempted due to the team's safety restrictions.

Enabling the MFSMC resulted in all level 1 ratings for the distant tracking task. The pilot comments described a well flying aircraft in all configurations but noted that the response was "rampy" at times. The term "rampy" indicated a pitch rate response which appeared to lag the input and grow over time rather than match the pilot input. Overall the MFSMC made configurations B, C, and D perform better in the distant tracking task while allowing configuration A to still achieve level 1 handling quality performance.

The close tracking task required the test aircraft to fly in close formation with the T-38C target while the target made

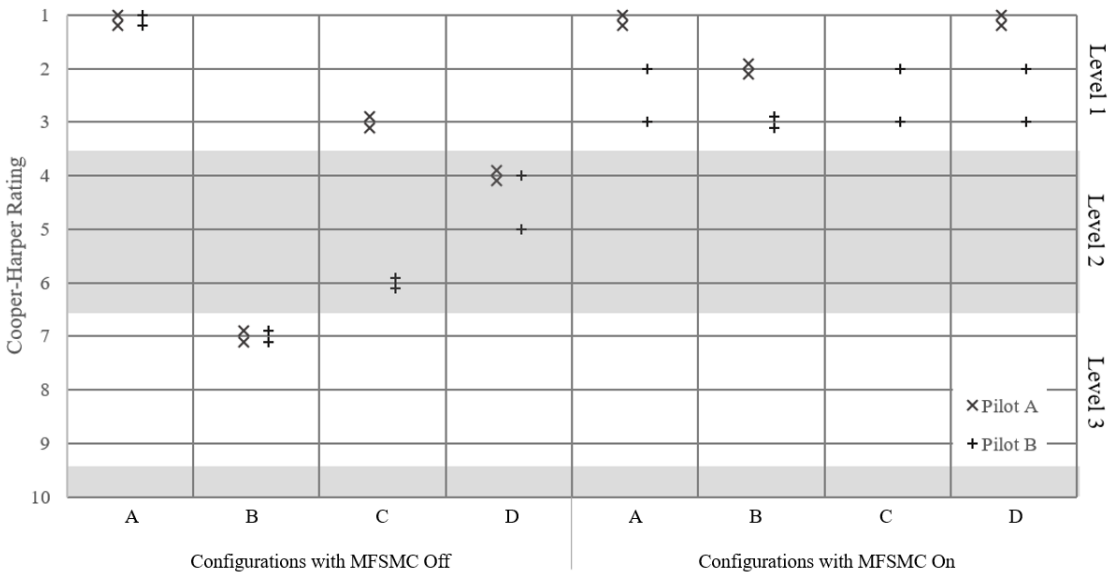

Fig. 9 Distant Tracking Task Handling Quality Ratings

small pitch bobbles of $0.8g - 1.2g$. The close tracking task utilized a common aircraft formation flying landmark, the wingtip, for its tracking criteria. The target aircraft was flown within XX ft of the T-38C target and the wingtip kept within the desired or adequate criteria. The desired and adequate criteria for the close tracking task are presented in Fig. 10

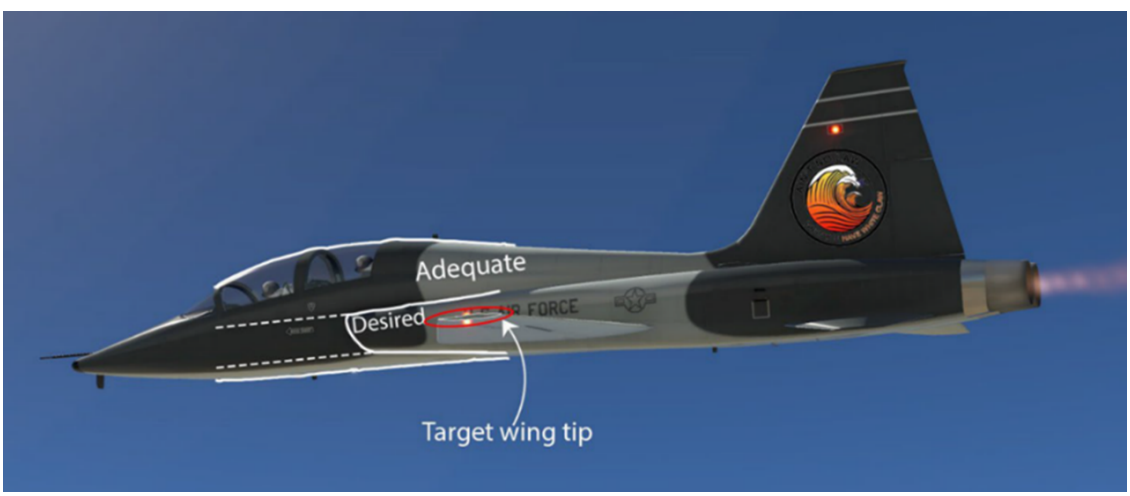

Fig. 10 Desired and Adequate Tracking Criteria

The close tracking task ratings are presented in Fig. 11. The handling qualities ratings with the MFSMC off were similar to the distant tracking task, as expected. Of note, pilot-induced oscillations were experienced in configurations C and D. The close tracking task ratings with the MFSMC on were qutie different from the ratings during the distant task. The clear observation is that the MFSMC received worse handling qualities for every configuration in the close tracking task. Pilot-induced oscillations were experienced in configurations A,B, and D; recall configuration A should be a well flying aircraft. The common pilot comment was that the evaluator had to work hard for these configurations and the aircraft was perceived to be sluggish. The team concluded that the "rampy" response observed in the distant tracking task and the "sluggish" response in the close tracking task could be attributed to the equivalent time delay observed during the frequency sweep analysis, Table 3.

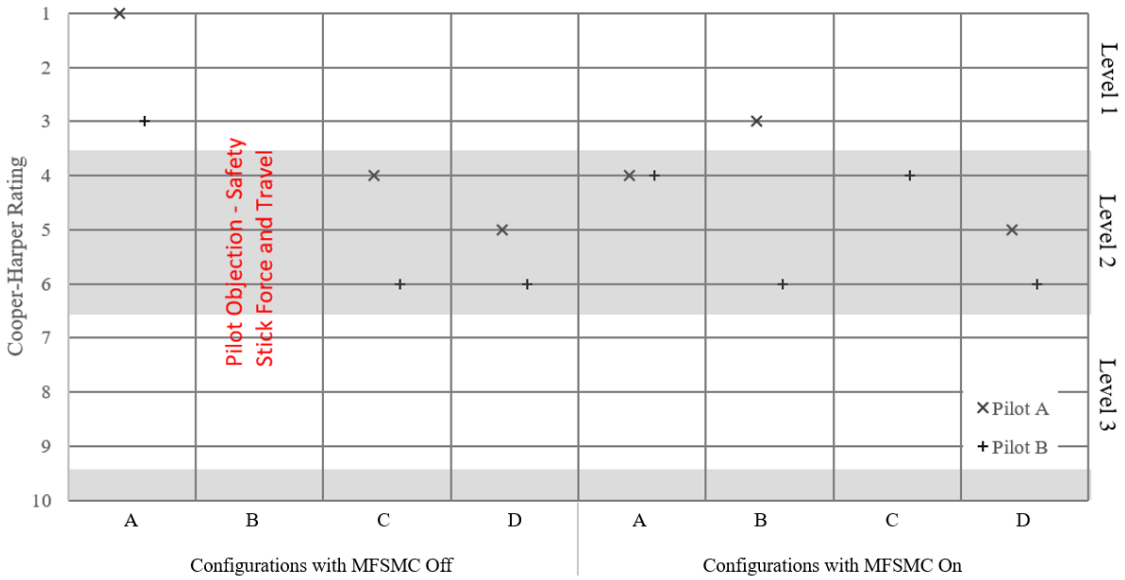

Fig. 11 Close Tracking Task Handling Quality Ratings

V. Challenges and Lessons Learned

This testing presents the unique challenge of model following controls in that the objective is not to evaluate what the flying and handling qualities are, but how closely they match the desired dynamics. This led the team to tailor to both quantitatively and qualitatively measure the test aircraft with the MFSMC both engaged and disengaged to evaluate the relative differences. Like in many test programs, the initial software version did not perform exactly as expected. In the case of this testing, the initial version of the MFSMC installed on the aircraft resulted in oscillations which would disengage the VSS.

The overarching cause of these oscillations was not able to be determined over the course of the two-week test window. However, the team developed a tuning plan which occurred over two flights in two days. The goal of this process was to find a configuration which could be tested in order to meet the learning objectives of the test pilot school curriculum. The model-free sliding mode control law is by no means a simple controller and the team identified 9 different parameters which could affect the behavior of the controller.

Ideally, the system designer would fly in the aircraft and modify parameters while the test pilots performed basic flying qualities maneuvers. This capability was available on the Calspan Learjet with the exception that the system designer was unavailable to travel during the test window. Instead, the team worked with the system designers and crafted a flow chart method to vary parameters one at a time in a controlled method, shown in Fig. 12. This unique method allowed the designer's insight to drive the tuning process without the need for the designer to be present in the test aircraft. After two flights, the team found an acceptable configuration which was frozen for the remaining testing. The capability to tune parameters on the fly and the unique approach to this problem enabled the team to "fly, fix, fly" multiple times in a single sortie.

VI. Conclusion

Overall, a new, untested control law was able to be flown on a manned aircraft for the first time within a safety envelope which eliminated the need for extensive safety planning. The initial test campaign lasted only two weeks but the test was able to simulate flight onboard four vastly different types of aircraft. The team was able to evaluate both the controller's flying qualities with respect to the desired dynamics model. Additionally, the team stressed the controller through distant and close formation flying tasks to explore the handling qualities of this flight controller. The results of the test highlighted both benefits and shortcomings of the design of the controller. The controller was able to reproduce the desired dynamics of the reference model but, that model had design features which degraded the resulting handling qualities. A full test program would be able to use these results to quickly update the design of the controller, repeat a subset of the testing and potentially develop a satisfactory solution. This demonstrates the benefits of risk reduction

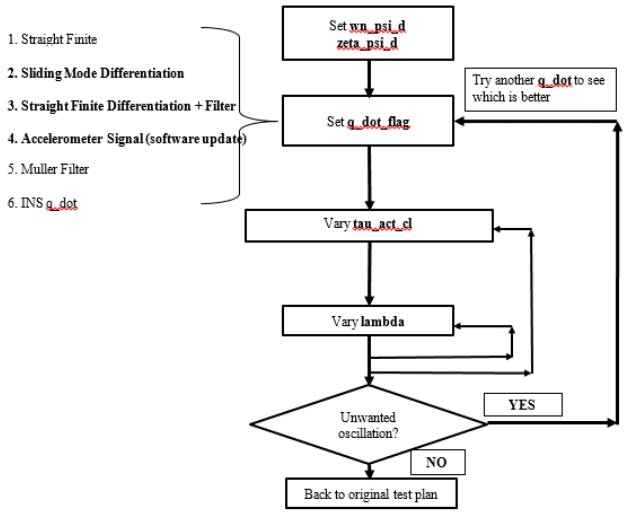

Fig. 12 Parameter Adjustment Method

aircraft to developing advanced flight control systems.

Acknowledgments

The test team would like to thank the Calspan team at Edwards Air Force Base for their hard work and support during this test project. The team would specifically like to acknowledge the two Calspan safety pilots, Andrew Edgell and Rigel Hebmann.

References

[1] Stevens, B. L., Lewis, F. L., and Johnson, E. N., *Aircraft Control and Simulation: Dynamics, Controls Design, and Autonomous Systems*, John Wiley Sons, Inc, Hoboken, NJ, USA, 2015. https://doi.org/10.1002/9781119174882, URL http://doi.wiley.com/10.1002/9781119174882.

[2] Grande, R. C., Chowdhary, G., and How, J. P., "Experimental Validation of Bayesian Nonparametric Adaptive Control Using Gaussian Processes," *Journal of Aerospace Information Systems*, Vol. 11, 2014, pp. 565–578. https://doi.org/10.2514/1.I010190.

[3] Rafi, M., Steck, J. E., and Watkins, J., "Kalman-Filter-Based Adaptive Control: Flight Testing on General Aviation Aircraft," *Journal of Guidance, Control, and Dynamics*, Vol. 40, 2017, pp. 2307–2315. https://doi.org/10.2514/1.G002693.

[4] Crassidis, A., and Reis, R. M., "Model-Free Sliding Mode Control Method," *International Conference of Control, Dynamic Systems, and Robotics*, 2016. https://doi.org/10.11159/cdsr16.100.

[5] Crassidis, A., and Tin, F. E., "A Model-Free Control System Based on the Sliding Mode Control Method with Applications to Multi-Input-Multi-Output Systems," *International Conference of Control, Dynamic Systems, and Robotics*, 2017. https://doi.org/10.11159/cdsr17.119.

[6] "MIL-STD-1797B: Flying Qualities of Piloted Aircraft," Tech. rep., United States Department of Defense, 2006.

[7] Cooper, G. E., and Harper, R. P., "The Use of Pilot Rating in the Evaluation of Aircraft Handling Qualities," Tech. Rep. NASA TN D-5153, National Aeronautics and Space Administration, 1969.

[8] Navarro, M. A., Ban, K., Fischer, J. P. A., Pelletier, M.-A. C., Sick, T. J., and Trautschold, M. G., "Limited Evaluation of a Model-Free Control Law System," Tech. Rep. USAFTPS-TIM-21B-02, United States Air Force Test Pilot School, 2022.