5-1-2021

Display Design to Avoid and Mitigate Limit Cycle Oscillations on the F-16c

David Feibus

DISPLAY DESIGN TO AVOID AND MITIGATE LIMIT CYCLE OSCILLATIONS ON THE F-16C

Captain David Feibus
Air Force Institute of Technology
Wright Patterson Air Force Base, OH

The U.S. Air Force F-16C's flight envelope is defined by its external weapon stores configuration, and the employment of some munitions at certain speeds can cause the F-16 to enter a flutter-like state called Limit Cycle Oscillations (LCO). In LCO, the pilot experiences turbulent vibrations reducing their fine motor control. The current research attempted to help pilots anticipate an LCO-susceptible configuration by projecting the consequences of employing certain munitions. It was hypothesized that the new displays would result in fewer flight envelope violations, fewer LCO occurrences, and increased situation awareness. The results show that there are situation awareness benefits if the pilot is not task overloaded, but the performance results were inconclusive. Further design maturation is necessary to understand the implications of the new display.

The flight envelope of the F-16, also known as the operating bounds in terms of airspeed, altitude, and wing loading, is dynamic. The addition or deployment of underwing-stored missiles, bombs, fuel tanks, sensors, or other devices changes the aerodynamic properties of the vehicle as well as the recommended flight envelope. Violation of the flight envelope incurs maintenance and sustainment impacts but does not constitute immediate structural failure.

A particularly problematic state occurs when wing tip missiles, typically air to air missiles, are employed. In the F-16, mass located at the wingtip damps oscillation of the wings. Thus, deploying stores from the wingtip can lead to turbulent oscillation of the wings and aircraft, known as Limit Cycle Oscillations (LCO). LCO is non-catastrophic and is closely linked to classical flutter but does not diverge (Bunton & Denegri, 2000). LCO causes loss of a pilot's fine motor control and reduces visual acuity like low frequency vibration due to flutter (Tung et al., 2014). To recover from LCO, a pilot must reduce airspeed and wing G-loading. As this is not a problem in today's mostly Air-to-Ground wars where the United States and enjoys air superiority, it presents a potential issue should the F-16 be employed in Air-to-Air battles. The flight envelope depends on the mass and drag properties of the underwing-stored articles, which defines the current and future flight envelopes, where a particular future envelope, referred to as the downloaded envelope, takes effect immediately after expending or jettisoning a store.

A pilot can be within their current flight envelope but have an airspeed that is beyond the downloaded envelope's limits, and when a missile is deployed, the F-16 will be operating outside its new designed flight envelope and will experience heavy LCO without warning. This research seeks to develop display symbology which improves the pilot's situation awareness (SA) by aiding their understanding of current circumstances, anticipating the impact of deploying a wing-stored article, and permitting them to project future actions (Endsley, 1995). As the pilot may intentionally violate the downloaded limits this research will additionally explore the use of status or command displays to aid recovery from LCO or other flight envelope limits. In the experimental evaluation of the design alternatives developed in this research, it was hypothesized that showing pilots their current and future envelope limits will enhance their SA and reduce both number and duration of flight envelope violations. It was also hypothesized that a status display would be more effective than a command display for recovering from LCO by enhancing the pilot's SA, allowing the pilot to make more educated decisions about this secondary task and avoid task overload (Weinstein & Wickens, 1992).

Method

The research method consisted of three phases. First, extensive interviews of Subject Matter Experts (SMEs) from a Flight Test Squadron were conducted using the Cognitive Work Analysis method. Second, display prototypes were developed and reviewed by SMEs. Last, an experiment was designed and conducted to test the effect of the displays on SA and performance.

Design Method

From the Cognitive Work Analysis, the pilots' needs, operational constraints, and environment resulted in the main design goal: to take the limits out of the pilot's head and put them into the world, as Norman suggests (Norman, 1988). Pilots expressed a strong interest in quickly cross referencing the current and future flight limits, and desired a display that operates in the background and not consume unnecessary real estate on the already-crowded displays.

The display consisted of two elements: Predictive Feedback (PF), and LCO Recovery (LR), when combined create the LCO Support System. PF used common SA design criteria, including supporting knowledge of both the current and future envelope limits to help pilots understand the consequences of their actions on their flight envelope. The PF display showed the current munition selected, if they were at risk for future LCO based on the current munition, and the current and future envelope limits in Mach and airspeed. The yellow wingtip missile in Figure 1 below shows that if that missile is selected, they will still be beyond their download limits and continue in LCO.

The LR display provided feedback to show the pilot that they were out of their flight envelope and a change in their flight conditions was necessary to recover. The LR display consisted of a colored banner with either a status or a command message telling the pilot they are OOB, and if LCO was present. A yellow banner meant the pilot was past the download limits based on the currently selected munition, and a red banner meant they were in LCO or OOB. These two elements were combined to create the LCO Support System for the experiment, as shown below in Figure 1.

Figure 1: The left side shows the download envelope (DWN), and the right side shows the current envelope, both based on the current missile selected (shown in white). The LR banner appears when the participant was either: currently experiencing LCO, past their download limits, or out of bounds of their current flight envelope.

Ideally an indicator of LCO would be available in the Heads-Up Display (HUD), similar to all other important flight information. However, the Center Display Unity (CDU) was the target display due to its easily modifiable architecture. The top of the CDU's screen was ideal for two reasons: First, it was determined that with a helmet and oxygen mask on, the bottom half of the CDU was obscured, requiring the pilot to move their head to crosscheck the display. No other major alert on the F-16 requires head movement which might be difficult under high G maneuvers. Second, the turbulent motion induced by LCO disturbs the vestibular system making displays farther from the resting visual angle of the HUD difficult to read.

Experimental Design and Procedure

The experimental design was a three-by-two-by-two, mixed-subjects, experimental design including the within-subjects variables of LCO Support (off or active), and the Scenario (1, 2, or 3), and the between-subjects variable of the Display Type (Status or Command). The Display Type was randomly assigned. The participants were tasked to fly a flight simulator and achieve air superiority against several Sukhoi Su-27 aggressors. Their secondary task was to stay within the flight envelope. The simulated scenarios were derived from real training missions.

The simulated F-16 was loaded with 4 long range and 2 short range Air-to-Air missiles. To ensure an LCO-susceptible configuration would be entered, participants were told their wingtip missiles were “superior” long range missiles and should be used first. Participants were invincible but instructed that 50 points were subtracted if they were hit, and 100 points were awarded for each kill. Their overall scores were collected to understand their performance.

Before the experiment began, each participant was first familiarized with employing air-to-air missiles using the F-16 interfaces and displays. Next, they were briefed on the envelope restrictions for the loadout for the experiment. Participants then flew a training scenario in which they had to face multiple enemies, from a starting distance of 45 nautical miles (nm), but without LCO Support and were encouraged to redo the training scenario until they felt comfortable.

Participants flew three different scenarios, each time flying the control case first with LCO Support inactive, and then flying the scenario with it active. The starting distance from the enemies decreased with each scenario, starting at 45 nm, to 30 nm, to 15 nm. The SAGAT method was used to measure SA by pausing the scenario during high points of stress: when focused on trying to fire a missile, evade an enemy missile, or for the missile’s radar to go active. Once the scenario was paused, participants were asked to answer questions about their flight envelope, the state of the scenario, and their aircraft. Lastly, an end survey asked for feedback on the CDU design, as well as HUD designs.

Participants

Nine males with flight experience volunteered from among the military and civilian workforce on Wright-Patterson Air Force Base. Participants included two active and three retired F-16C pilots with an average of 1950 flight hours. Additionally, two active F-15 pilots with an average of 1160 flight hours, and two participants with general flight experience participated.

Apparatus

Digital Combat Simulator (DCS) 2.5.6 was used for the flight simulator, using an F-16C Block 50 airframe. Unity was used to create the LCO Support System and CDU. A Thrustmaster Hands on Throttle and Stick (HOTAS) Cougar was used. An LG 65” TV was used to display DCS, and the CDU was displayed using a ViewSonic VG2455-2k 24” Monitor. The participant was seated 29 inches away from the CDU, mimicking the viewing angle present in the F-16C, without needing to recline the chair. Participants were not allowed to use the unreliable Missile Step button on the HOTAS to switch between missiles of the same type to avoid a possible disparity between DCS and Unity. The Fire Control Radar (FCR) cursor was augmented to include the option to either use the left index finger or thumb, accounting for the HOTAS differences in the F-16 and the F-15.

Metrics

All variables were subjected to a mixed factor ANOVA. Score within each scenario as well as envelope violations and durations were collected for the LCO and OOB conditions, respectively. SAGAT scores were scaled by multiplying incorrect answers by -1 and correct answers by 1, and a confidence rating was collected for each SAGAT response on a 1 to 5 scale.

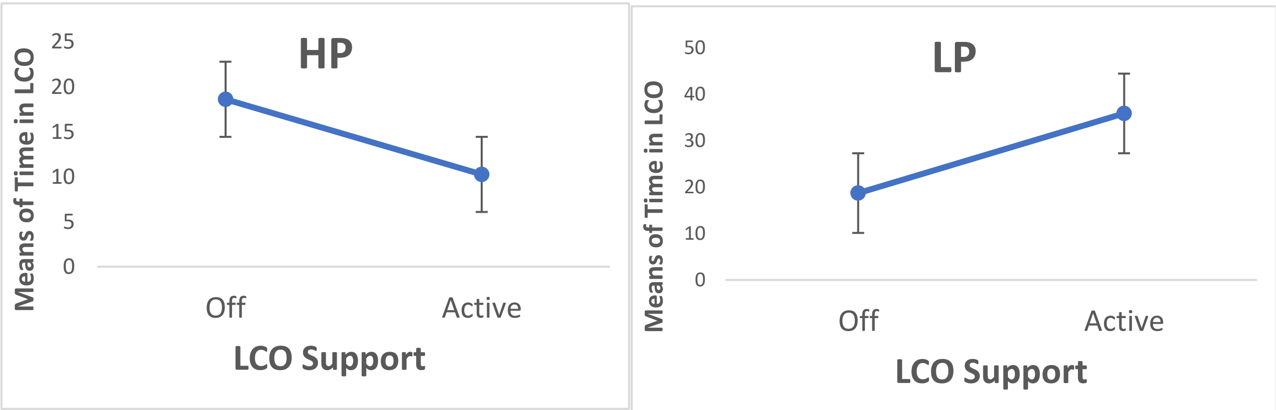
Results

It was expected that participant familiarity with the F-16 would lead to superior performance, but there were no statistically significant results on the sample population. For analysis, the population was divided into two groups: 5 High Performers (HP) and 4 Low Performers (LP). This was based on the sum of their total scenario scores being above or below the mean. The current F-16 and F-15 pilots were classified in the HP group while the general aviation participants fell within the LP group. Surprisingly, two of the retired F-16 pilots were classified in the LP group.

Performance

LCO support had a significant effect on the mean duration of LCO envelope violation for the HP group (F (1, 3) = 18.071, MSE = 26.84, p = 0.024, η_p^2 = 0.858). As shown in Figure 2, the mean duration of LCO envelope violation decreased for the HPs by 8.21 s (SD = 1.93), in accordance with the hypothesis. LCO support also had a significant effect on the mean duration of LCO envelope violation for the LP group (F (1, 2) = 38.682, MSE = 45.68, p = 0.025, η_p^2 = 0.951). However, for the LPs it significantly increased by 17.16 s (SD = 2.77), counter to the hypothesis.

The ANOVA indicated a significant increase in the number of LCO violations for the LP group (F (1, 2) = 81, MSE = 0.01, p = 0.012, η_p^2 = 0.976) as shown in Figure 3. The number of LCO violations was not significant for the HP group (F (1, 3) = 0.008, MSE = 0.73, p = 0.93, η_p^2 = 0.003). There was also no effect of LCO support on the total number of envelope violations (LCO or OOB) for either the HP group (F (1, 3) = 0.692, MSE = 1.81., p = 0.466, η_p^2 = 0.187) or the LP group (F (1, 3) = 5.31, MSE = 1.89, p = 0.148, η_p^2 = 0.726).



.

Figure 2: LCO Support versus Mean Time spent in LCO, where lower values are desired. Error bars represent the standard error.

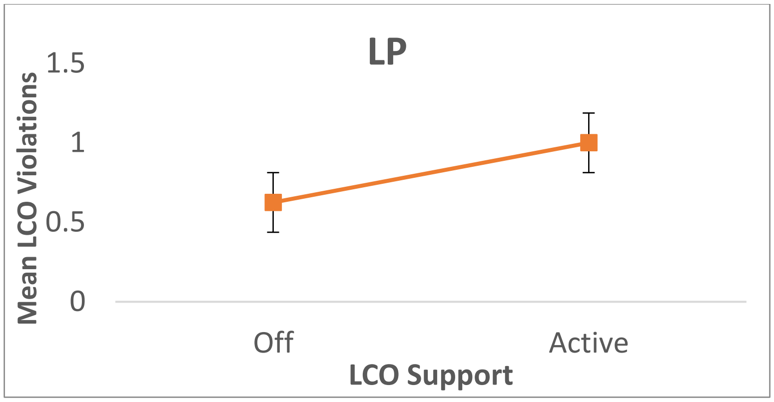


Figure 3: LCO Support versus Mean LCO Violations for the LP group, where lower values are desired. Error bars represent the standard error.

Situation Awareness and Display Aids

It was expected that LCO Support would yield large SA benefits, but due to the small sample size there were no significant main effects of LCO Support for either group on the SAGAT questions. The HP group's mean number of correct answers and confidence levels increased with active LCO Support, while the LP group's both decreased. From the interaction of LCO Support and Display Type, there were no significant main effects on either group. While it was expected that the group using the Status display would have greater SA and performance, participants consistently could not recall the content of the LCO Recovery banner indicating that the type of display did not have an effect. Most participants reported they did not have time to read the LCO Recovery banner during the intensive scenarios but relied on the color of the banner to determine their status in the flight envelope.

Discussion

The current research explored the application of a predictive feedback display to project a participant's future state after employing munitions, permitting pilots to make changes to their tactics to avoid inducing LCO. It was theorized that this system would change the task structure for the pilot, replacing the working memory required to recall the dynamic envelope limits with a simple item added to a pilot's normal instrument crosscheck. On average, pilots in a high performing group reduced the time they violated the flight envelope while participants in the low performing group tended to violate the flight envelope limits more and for longer durations when LCO Support was active. The research provided evidence that, if not task saturated, the participant's SA will benefit from the new display, as was true for the HP group.

The experiment did not simulate the negative LCO consequences, such as display shaking or flight control issues, so participants had no true incentive to avoid LCO. With LCO consequences, a participant may have been more willing to adjust their tactics and an improvement in performance might have occurred. Real feedback would update the participant's mental model of their aircraft and permit them to experience the weight of their decisions. The F-

16's FCR in DCS also displayed unreliable performance, randomly losing radar lock on enemies at critical moments in the kill chain, forcing a closer engagement and exacerbating an already stressful and difficult situation, leading to poorer performance.

It is possible the participants needed more exposure and training on the new display before being subjected to difficult scenarios. Participants in this experiment had to contend with their envelope limits throughout the entire scenario, which is not operationally representative. The desired outcome of the integration of this display is to augment training and influence the use of weapons deployment strategies to reduce the likelihood of LCO.

While participants liked the design and said that without LCO Support it required too much mental energy to stay within the limits and be tactically effective, participants said the design still required some maturation and fine tuning before fielding. The flashing color acted as truth data, updating the mental models of the participants, especially those who were unaware of their position in the envelope. All participants expressed an affinity for LCO Support indicators in the HUD, and felt the design was incomplete otherwise.

Due to experimental limitations, the performance results are inconclusive which demonstrates a need for a higher fidelity experiment with actual LCO consequences. Such a system may provide additional performance and SA advantages to the pilot, but further design maturation is required. Additionally, the research suggests that without indicators in the HUD, the high workload which occurs prior to LCO onset may prevent one from receiving information from the CDU. As a result, further research is required using a higher fidelity apparatus to determine the impact of LCO Support on a pilot's performance and SA.

Acknowledgements

The author would like to thank the F-16 System Programs Office for motivating this research, as well as the 40th Flight Test Squadron for their many hours of SME time for their assistance in creating the experimental designs and research method. The views in this article are those of the authors and do not necessarily reflect the official policy or position of the Department of the Air Force, Department of Defense, nor the U.S. Government.

References

Bunton, R. W., & Denegri, C. M. (2000). Limit cycle oscillation characteristics of fighter aircraft. *Journal of Aircraft, 37*(5), 916–918. https://doi.org/10.2514/2.2690

Endsley, M. R. (1995). Toward a theory of situation awareness in dynamic systems. *The Journal of the Human Factors and Ergonomics Society, 37*(1), 32–64. https://doi.org/10.1518/001872095779049543

Norman, D. (1988). *The Design of Everyday Things: Revised and Expanded Edition - Kindle edition by Norman, Don. Health, Fitness & Dieting Kindle eBooks @ Amazon.com.* Basic Books.

Tung, K., Miller, M., Colombi, J., Uribe, D., & Smith, S. (2014). Effect of vibration on eye, head and helmet movements while wearing a helmet-mounted display. *Journal of the Society for Information Display, 22*(10), 535–544. https://doi.org/10.1002/jsid.286

Weinstein, L. F., & Wickens, C. D. (1992). Use of Nontraditional Flight Displays for the Reduction of Central Visual Overload in the Cockpit. *The International Journal of Aviation Psychology, 2*(2), 121–142. https://doi.org/10.1207/s15327108ijap0202_4