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Development of the Probe-and-Drogue Handling Qualities Demonstration Maneuver

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The development of the probe-and-drogue aerial refueling task as a handling qualities demonstration maneuver is described. The probe-and-drogue task is an excellent test of handling qualities for precision flying and is also a superb check for pilot-induced oscillation tendencies. The greatest difficulty with this maneuver has been in the definition of the task itself including the definitions of specific performance limits. The task described herein differs from that described in the Notice of Change to Flying Qualities of Piloted Aircraft (MIL-STD-1797A) in that it requires precise drogue tracking in addition to a percentage of successful hookups. A task representative of that defined in MIL-STD-1797A that required at least three hookups in six attempts for desired performance was used as the evaluation method for the HAVE GAS project conducted by the U.S. Air Force Test Pilot School. This version of the maneuver, however, was found to be too easy even for poorly rated airplanes. Revised maneuver descriptions and performance requirements were developed and evaluated in the HAVE GAS II project that was undertaken as part of the U.S. Air Force Demonstration Maneuvers program and again conducted by the U.S. Air Force Test Pilot School. Three candidate tasks were evaluated in this test program: 1) the probe-and-drogue hookup task, 2) a new drogue tracking task, and 3) a new drogue pointing task. Although the drogue tracking task was found to be best for evaluating closed-loop handling qualities, it was limited by the fact that it would not reveal potential problems such as bow-wave effects that may be encountered within 5 ft of the basket. Thus it was concluded that a combination of the drogue tracking task and the probe-and-drogue hookup task should be flown to thoroughly evaluate closed-loop handling qualities in the aerial refueling mission.

Introduction

IN any aircraft development program demonstration of acceptable handling qualities begins with quantitative requirements but, ultimately, relies on qualitative pilot assessment. The combined importance of valid analytical criteria and meaningful flight demonstration maneuvers has resulted in a focused effort to document a set of maneuvers that can be performed in a consistent manner. To this end, the probe-and-drogue aerial refueling task is a good test of closed-loop handling qualities. There has been little effort, however, to formalize the task so that the description of the maneuver and related performance definitions are documented.

Aerial refueling with a probe-equipped airplane is common in the U.S. Navy whereas U.S. Air Force airplanes typically use refueling nozzles from the boom of the tanker. The difference in demands on the pilot of the receiver aircraft can be significant. Whereas the boom operator must maintain position within tight tolerances, the demands on the receiver pilot tend to be much lower than those required of a pilot performing an approach and final plug-in with a refueling probe. In the probe-and-drogue task the pilot is required to position-keep while initiating contact with a target that may or may not be stable, and the ramifications for even small errors can be significant. Location of the refueling basket on the tanker, size of the basket, location and shape of the refueling probe on the receiver, and airspeed at which the refueling is performed can all introduce variability into the task. Unfortunately, all of these variables also make it difficult to define a precise maneuver that is applicable to any combination of tanker and receiver.

This paper presents the evolution of the probe-and-drogue task into a suitable handling qualities demonstration maneuver. It includes a detailed discussion of the HAVE GAS II flight-test program that was conducted specifically to define and evaluate variations of the probe-and-drogue task for their use as demonstration maneuvers.[1,2]

Background Experience

Navy Experiences from the F-14 Simulated Dual Hydraulic Failure Flight-Test Program

In a handling qualities study of the F-14 with simulated dual hydraulic failure, the U.S. Navy evaluators focused on probe-and-drogue refueling.[3] The tanker chosen was an A-7 "due to cost, availability, and its notoriety as the worst case tanker platform." Probe-and-drogue refueling with the Stability Augmentation System (SAS) off was relatively uneventful, with two successful engagements in six attempts. With hydraulic power turned off, however, the explosive nature of the task was quickly exposed during the first attempts at engagement, starting with

> ... close parade and column formation. Maintaining proper vertical position ±1 ft was very easy and assessed as an (Cooper–Harper) Handling Qualities Rating (HQR)-2. The final criteria for proceeding to basket engagement was satisfied during the approach to contact, having demonstrated that the pilot could stabilize the probe within $\frac{1}{2}$ basket radius while 10 ft in trail. Upon the first contact, a mild pilot-induced oscillation (PIO) ($\sim\frac{1}{2}$ Hz) developed in pitch, which threatened to diverge, and the pilot quickly disengaged. The pilot attributed this PIO to personal technique and decided to reattempt engagement. The approach to the second engagement was very smooth and steady .... Upon contact, the airplane immediately started to diverge in pitch with four oscillations complete prior to successfully disengaging .... Lateral control was likewise lost with the airplane 85° right wing down at disengagement. Once clear of the tanker, depression of the

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nose wheel steering switch immediately restored normal hydraulic power.[3]

Although this particular incident was the result of a known deficiency (very low actuator rate limit), it is a dramatic indicator of the possibly explosive and insidious nature of the task because close-formation flight gave no hint of the handling qualities cliff that was to come. The authors of Ref. 3 observed that "we had relied upon the formation task with ±1 ft tolerances to warn us of any adverse handling qualities prior to engagement. Instead of alerting us to the problem, the benign formation handling qualities using that tolerance had deceived us into believing that no problem existed." This series of events led the experimenters to devise a tracking drill "where the F-14 pilot was required to keep the probe aligned in trail of the basket while the tanker mildly maneuvered. Bank-to-bank rolls to 30° in each direction were envisioned with roll rates of about 5 degrees per second."

Experiences from the U.S. Air Force Test Pilot School HAVE GAS Project

In the fall of 1993, Class 93A of the U.S. Air Force Test Pilot School (TPS) conducted a study of the suitability of different response-types for the probe-and-drogue task.[4] The evaluation maneuver was essentially the hookup task documented in the current version of MIL-STD-1797A.[5] The formal task began with the evaluation aircraft (in this case the U.S. Air Force variable-stability NT-33A operated by Calspan Corporation) in precontact position 10–15 ft in trail of the drogue, with the probe in line with the drogue vertically and laterally. When cleared for contact, the pilot initiated a 3- to 5-kn closure rate and attempted to make contact. The pilot aborted his attempt if the closure rate stopped or exceeded 5 kn, the probe tip passed beyond the edge of the drogue, the probe tipped the basket, or safety was jeopardized. The goal was a minimum of three successful hookups per evaluation, with no maximum number of attempts specified. Performance was defined primarily in terms of the number of attempts to achieve the three successful hookups. Desired performance required no more than six attempts (50% or greater success rate), as well as a pilot-induced oscillation rating (PIOR) of no worse than 2; and adequate performance required no more than 12 attempts (25% or greater success rate) with a PIOR no worse than 4.

During the experiment, the evaluation pilots found these performance criteria to be ineffective at discriminating handling qualities. As stated in Ref. 4, "Due to the excellent stability of the drogue and the design of the refueling probe installed on the NT-33A, which placed the probe tip on the longitudinal axis of the aircraft and well ahead of any bow wave effects, the evaluation task was considered to be too easy by the project pilots. No more than six approaches were ever required to achieve three hook-ups." Graphical evidence of this is presented in Fig. 1, which summarizes the HQRs from the two pilots in comparison with the number of attempts required to achieve the three hookups. Ratings range from 1 to 9 even when only three attempts were required.

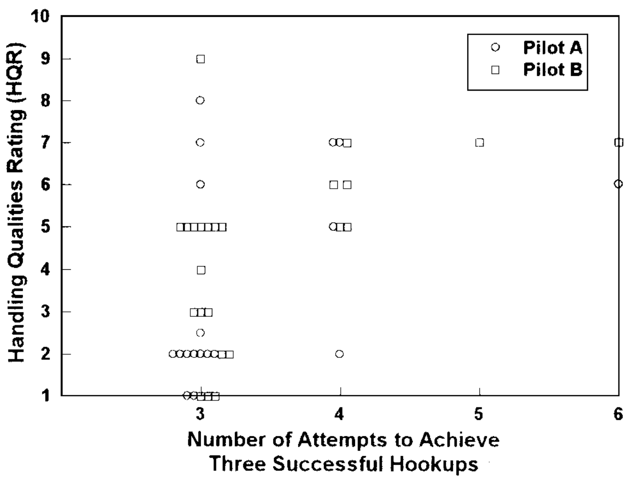

Fig. 1 HQR vs number of attempts to achieve three hookups (HAVE GAS Project, Ref. 4).

Although the results of HAVE GAS clearly indicated that a revision in the maneuver definition was necessary, they did not invalidate the probe-and-drogue task as a handling qualities maneuver; indeed, they support its use because the pilots were able to discriminate between good and poor handling configurations. The problem, rather, was that the handling qualities performance requirements did not aid in the qualitative evaluations made by the pilots. An alternative set of requirements was, therefore, needed.

In personal discussions with Capt. Michael Taschner (coauthor of Ref. 4), possible alternative tasks or requirements were discussed. At the conclusion of their formal evaluations, the pilots in the HAVE GAS project would perform a short precision tracking test: point the probe at the top, center, and bottom of the basket. Because this task had no defined performance requirements, it was not used in the evaluations, but Capt. Taschner felt that it was more effective at consistently exposing differences between the configurations. This tracking test was used in a manner similar to the tracking drill that superseded the close formation task in the U.S. Navy F-14 flight-test program already discussed. Both alternative tasks were designed to more consistently expose potential handling qualities deficiencies.

MIL-STD-1797A Maneuver

The 1995 revision to MIL-STD-1797A[5] includes probe-and-drogue refueling among the recommended evaluation maneuvers. The version given is essentially that flown in HAVE GAS, including the desired and adequate performance limits. The interface standard recommends 6–12 attempts, with desired performance consisting of "hook-up without touching basket webbing in at least 50% of the attempts" and "no PIO"; adequate performance is "hook-up in at least 25% of attempts." The additional Level 1 requirement to avoid touching the basket webbing was added in response to the results attained in the HAVE GAS project.

Demonstration Maneuver Development

HAVE GAS II Program Background

The HAVE GAS II test management project was conducted by Class 96B of the U.S. Air Force TPS in support of the U.S. Air Force Demonstration Maneuvers program. Personnel from prime contractor Systems Technology, Inc., and subcontractor Hoh Aeronautics, Inc., worked directly with the HAVE GAS II team in all phases of the flight-test program. The primary objective was to identify the task that best reveals aircraft closed-loop, probe-and-drogue handling qualities. Testing consisted of seven test sorties, 11.2 flight hours, and was conducted at Edwards Air Force Base, California, from April 17–22, 1997. Three pilots consisting of two project team members and one TPS instructor pilot participated in the program.

Three tasks were evaluated and compared in this program: 1) the probe-and-drogue hookup task from Ref. 5; 2) a new drogue tracking task inspired by the U.S. Navy F-14 Simulated Dual Hydraulic Failure program; and 3) a new drogue aiming task inspired by the U.S. Air Force TPS HAVE GAS project. The probe-and-drogue hookup task consisted of six attempts at probe hookup with the drogue. Performance was based on the percentage of successful hookups and whether the hookups could be accomplished without touching the basket webbing. The drogue tracking task required the pilot to track the center of the basket with the tip of the refueling probe. Performance was based on how precisely the pilot could track the center of the basket with the probe for a period of at least 20 s. Finally, the drogue aiming task required the pilot to precisely point the tip of the refueling probe onto the center, top, and bottom of the basket. Performance was based on how precisely the pilot could reposition and stabilize the probe onto the desired aimpoint. Further details regarding the task descriptions can be found in Appendix A of Ref. 2.

These tasks were performed with two different aircraft, a NASA F/A-18B and the U.S. Air Force variable stability NT-33A (operated by Calspan Corporation). Tanker support was provided by S-3Bs from North Island Naval Air Station, California. The intent of this program was not to evaluate the aircraft specifically, but rather to evaluate the effectiveness of the tasks in exposing probe-and-drogue refueling handling qualities deficiencies. The tasks were evaluated based on their ability to differentiate between aircraft of varying

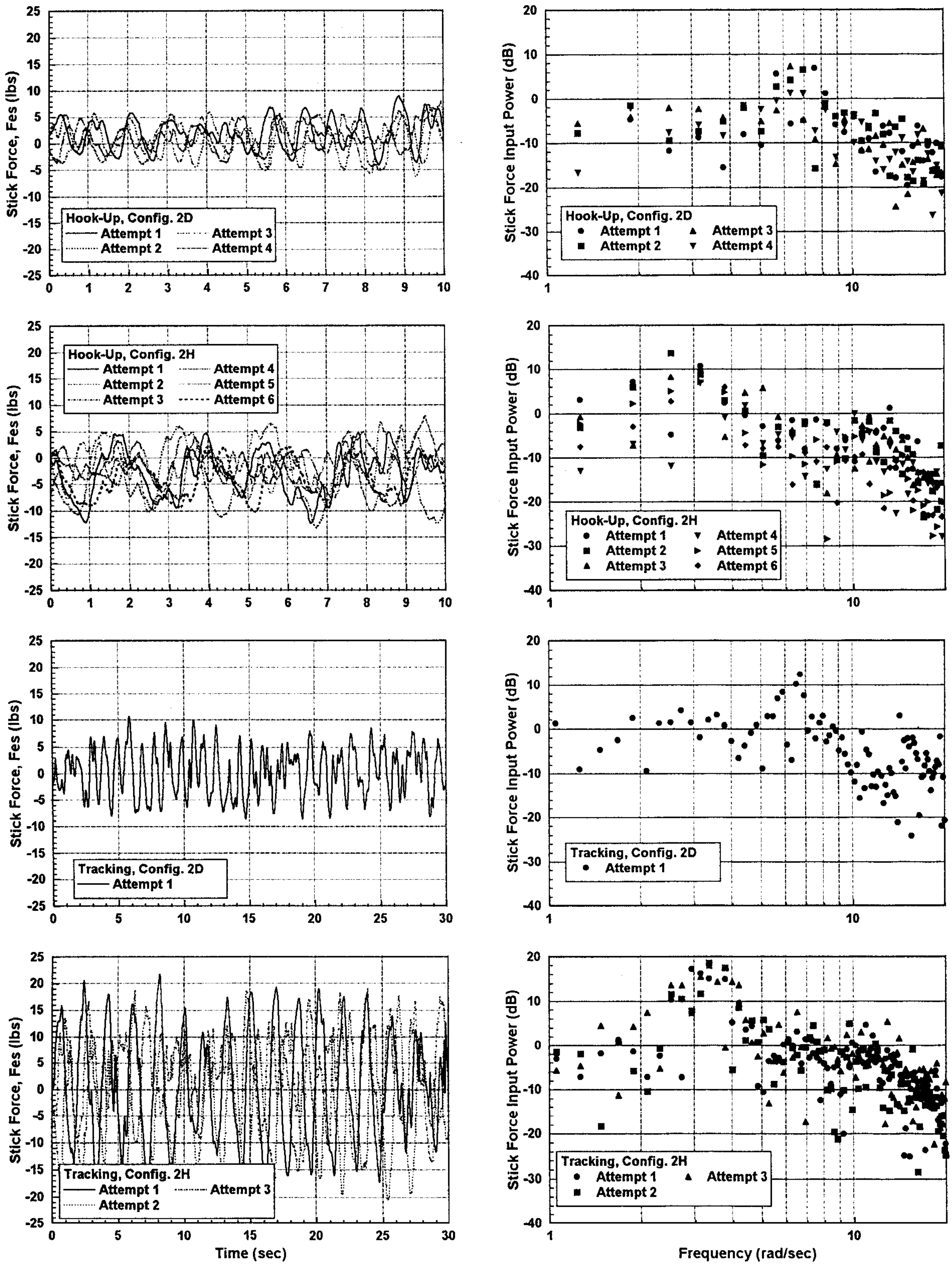

Fig. 2 Stick force time history and PSD plots from Pilot A NT-33A data sortie.

handling qualities levels, to provide consistent handling qualities ratings, and on the overall qualitative assessment of the tasks by the pilots.

Four sorties were flown with the NASA F/A-18B. Because the dynamics of this aircraft were fixed, these flights were used primarily to formalize the task definitions through variations in setup conditions and performance criteria. In particular, various distances for the drogue tracking and aiming tasks were explored. Three sorties were flown with the NT-33A. These flights were used to evaluate the refueling tasks with three different pitch configurations. The configurations were identified as 2D (expected to be Level 1), 2P (Level 2), and 2H (Level 3). Details of these configurations are provided in Ref. 1. Roll dynamics were not varied.

An observer in a chase plane assisted with estimates of the probe-to-drogue separation distance; this was considered to be a highly desirable method for assuring uniform task performance. In all cases,

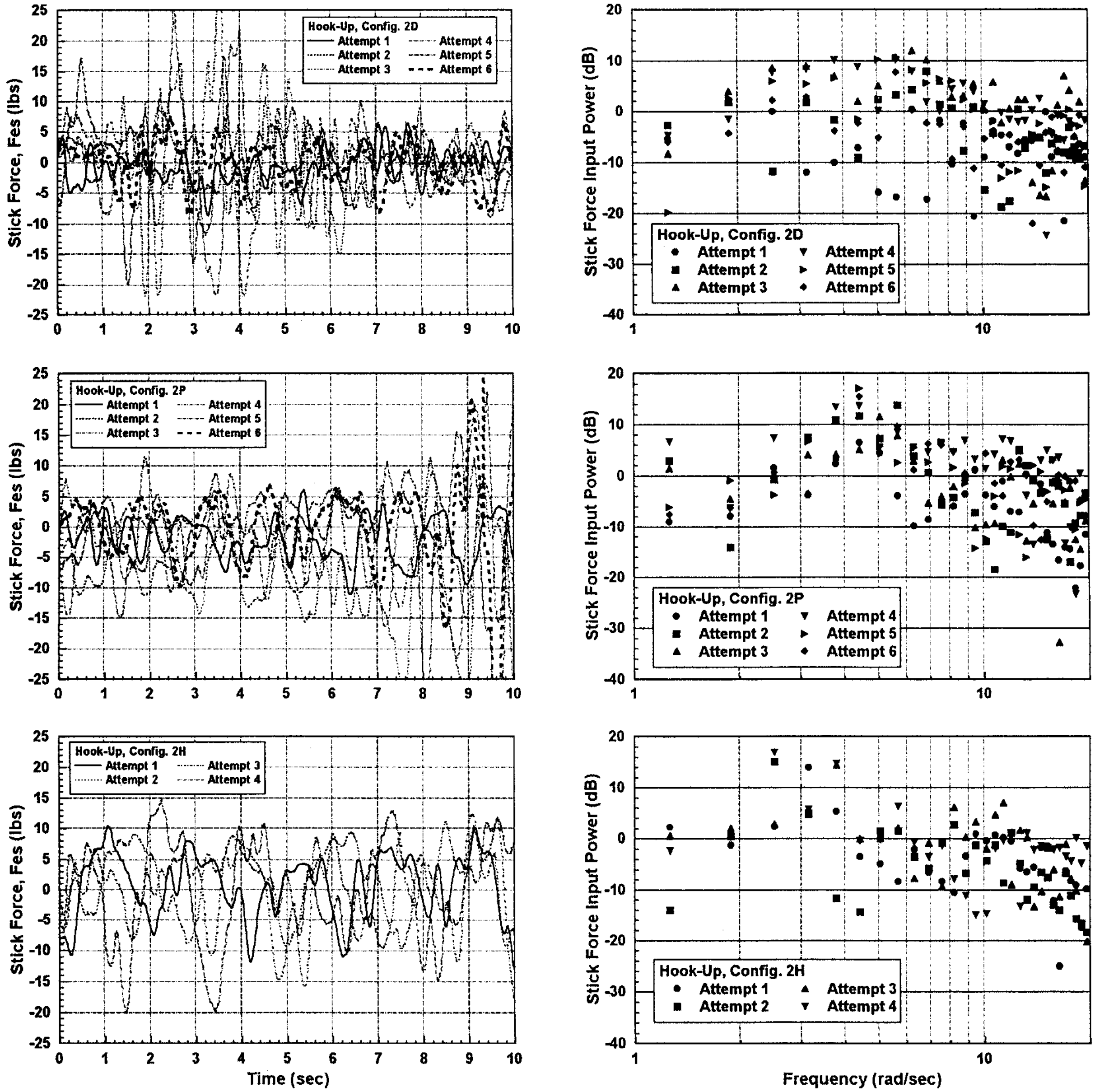

Fig. 3 Hookup task stick force time history and PSD plots from Pilot B NT-33A data sortie.

however, the evaluation and safety pilots in the test aircraft were able to make reasonably accurate estimates of separation that agreed with the observer's estimates. No attempt was made to formally measure, track, or verify the separation distances.

Qualitative Results

Hook-Up Task

All three pilots commented that the probe-and-drogue hookup was the most operationally representative task. Accounting for drogue webbing hits during air refueling helped differentiate between aircraft handling qualities levels by forcing the pilot to fly the task more closed-loop. In addition, any attempt at a last second, end-game correction by the pilot helped differentiate between good and bad handling airplanes. Of the three tasks flown, the hookup task was found to be the least susceptible to the effects of turbulence because the task description allowed the pilot to discount failed attempts resulting from basket motion. Probe placement on the evaluation aircraft had no effect on the task, but this may not be the case for all aircraft. Wake turbulence from the tanker was noticeable, but it did not affect the task. Bow-wave effects on the task were not evident. The specified 3- to 5-kn closure rate used in the task was acceptable.

The pilot comments also indicated that the hookup task did not reveal accurately aircraft closed-loop probe-and-drogue refueling handling qualities in all cases. In particular, given a Level 2 or 3 airplane, no turbulence and/or basket motion, and a stable setup 8–10 ft aft of the basket, hookups could be achieved without hitting the webbing, and this was accomplished by flying the task at very low gain and essentially open-loop. As the pilots gained experience with the task, they naturally developed a more open-loop technique. Unfortunately, opportunities to score a direct hit with the center of the basket through last second, end-game corrections were often discouraged by the open-loop nature of the learned task.

Tracking Task

The pilots assessed the drogue tracking task as moderately good to very good overall using the classifications defined in Ref. 2. The task was, however, only considered marginal as an operationally representative task. On one hand, the task represented lining up from the precontact position, whereas on the other hand, it lacked the true nature of probe-and-drogue refueling where last minute corrections near the basket may be necessary. Turbulence had a significant effect on the behavior of the drogue, which lowered the confidence of the pilots in the assigned HQR at all tracking distances although the effect was more pronounced at shorter tracking distances.

The pilots found the tracking task to be well defined with easy-to-determine handling qualities performance requirements.

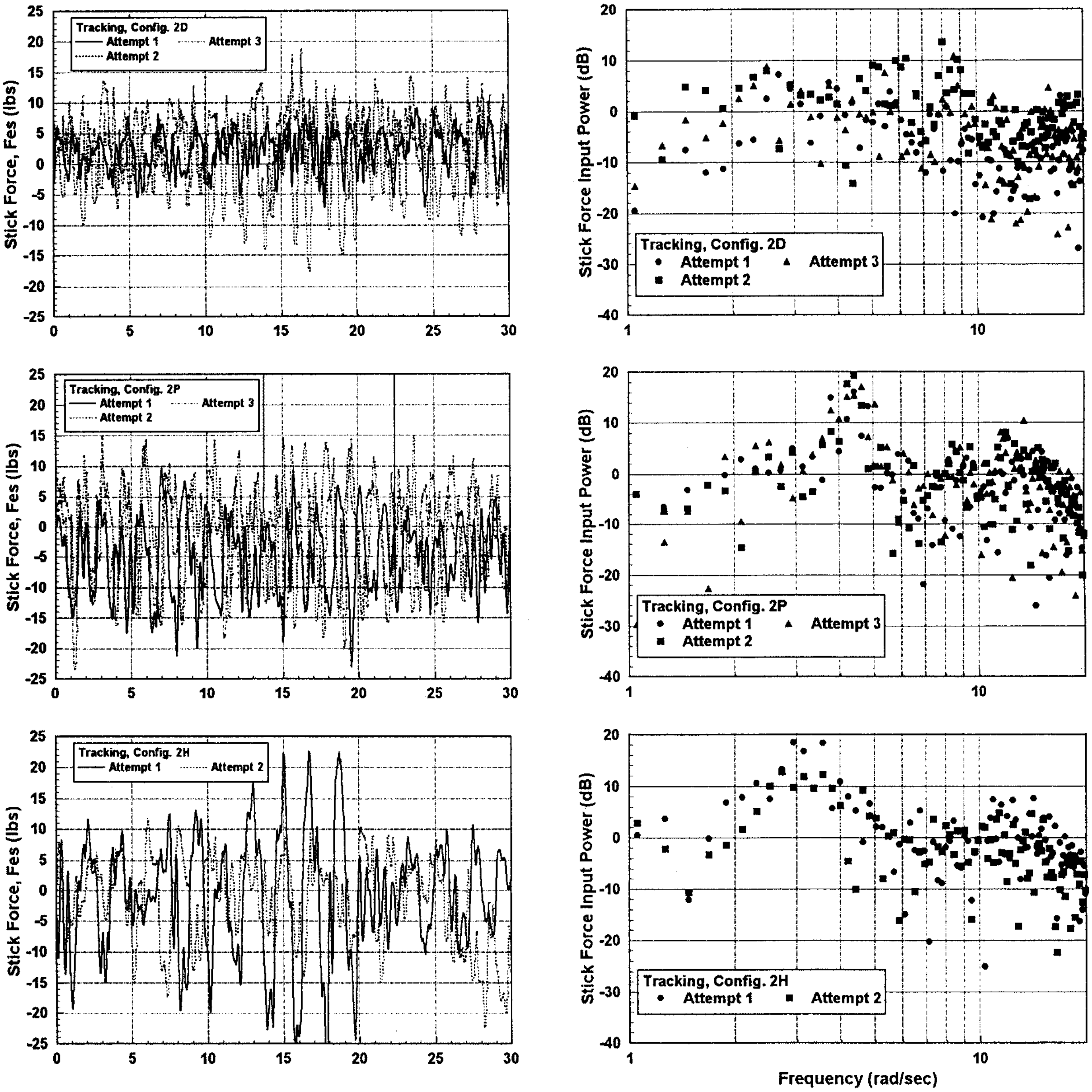

Fig. 4 Tracking task stick force time history and PSD plots from Pilot B NT-33A data sortie.

Throughout the test sorties the pilots agreed that the closer tracking distance (3–4 ft) was not a desirable setup for several reasons. First, it was less operationally representative in terms of a precontact position. Second, it had a higher potential for aircraft damage (especially for the F/A-18B where the probe tip is 6 ft aft of the nose). Finally, it often produced excessively high pilot gains. The best distance for tracking was 6–10 ft. A minimum tracking time of 20 s was required before an effective evaluation could be made. In some cases more than 20 s was required due to basket motion corrupting task performance. To accommodate these momentary excursions, the task was refined such that the tracking duration was at least 20 s, and as long as the pilot needed to assign an HQR with high confidence.

Aiming Task

The drogue aiming task had several common deficiencies that were noted by the evaluation pilots. First, it was highly dependent on pilot aggressiveness; i.e., more aggressive attempts resulted in degraded performance. Second, the handling qualities performance criteria were difficult to interpret in flight because overshoots of the aimpoint could result from a poor responding aircraft configuration or basket movements; this strongly contrasted with the drogue tracking task where the pilot attempted to hold the probe at a constant aimpoint. In the tracking case movements of the basket were easily discernable from undesirable aircraft motions. Finally, the task was found to be the least operationally representative of the three evaluated; i.e., the control inputs required to conduct this task were not representative of those used when conducting actual probe-and-drogue refueling, even when correcting for setup errors or basket movement.

Effect of Turbulence

The pilots observed that even in light turbulence the basket motion often made it difficult to accurately assess aircraft handling qualities. Although the impact of turbulence on task effectiveness was not formally evaluated, the pilots recommended that a rating scale which accounted for the effect of turbulence such as that shown in Table 1 (Ref. 6) should be used.

Quantitative Results

Having eliminated the aiming task via pilot commentary, a quantitative assessment was made of the remaining two tasks. This assessment included time and frequency domain longitudinal control force inputs for the two project pilots (identified as Pilots A and B) from their NT-33A sorties. Data from the TPS instructor pilot's sortie were not considered because stick sensitivity problems resulted in highly PIO-prone configurations for all evaluations.

PROBE-AND-DROGUE REFUELING

Objectives

- Evaluate ability to precisely control horizontal and vertical flightpath and airspeed.
- Evaluate ability to precisely control closure rate and attitude while refueling.
- Evaluate control sensitivity and harmony in close tracking.
- Identify tendency for nose bobble or PIO.

Description

Drogue Tracking: Stabilize the probe 6 to 10 ft aft of the basket. From this position, keep the probe within the edges of the basket for at least 20 seconds, using the center of the basket as the aimpoint, as shown in Figure 6. Repeat the task at least three times. Momentary excursions outside the desired or adequate limits that are considered to be a result of basket motion and beyond the control of the evaluation pilot should not be considered when assessing overall performance.

Drogue Hook-Up: From the pre-contact position, (10 to15 ft behind the drogue with the refueling probe in line both vertically and horizontally) establish a 3 to 5 kt closure rate and attempt to make contact. If the hook-up is successful, stabilize for approximately 30 seconds, then establish a 3 to 5 kt separation rate to disconnect and return to the pre-contact position. Repeat the task at least six times. A hook-up attempt is defined as an approach from 15 ft with intent to hook-up. If the closure rate stops or if the closure rate exceeds five knots, abort the attempt. If the probe tip passes the outside edge of the drogue basket or a hazardous situation develops, abort the hook-up attempt and return to the pre-contact position. Aborted attempts caused by momentary basket excursions due to turbulence will not be counted as an attempt.

If appropriate, use the turbulence effect rating scale to account for degradations in task performance due to turbulence.

Desired Performance

Drogue Tracking:

- Maintain the probe vertically and laterally within ½ basket radius of the aimpoint.
- No contact with the basket (unless sudden basket motion is caused by the tanker or external influences).

Drogue Hook-Up:

- Hook-up without touching basket webbing in at least 50% of the attempts.

Adequate Performance

Drogue Tracking:

- Maintain the probe vertically and laterally within one basket radius of the aimpoint.
- No contact with the basket (unless sudden basket motion is caused by the tanker or external influences).

Drogue Hook-Up:

- Hook-up in at least 50% of the attempts.

Variations

Alternate tracking distances may be employed depending on the location of the refueling probe on the evaluation aircraft.

Fig. 5 Probe-and-drogue demonstration maneuver description.[7]

Analysis of Pilot A NT-33A Sortie

Data from two of the three aircraft configurations (2D-Level 1 for both tasks evaluated by Pilot A and 2H-Level 3 for both tasks evaluated by Pilot A) were available for Pilot A. (Start and end times for the configuration 2P evaluations could not be determined from available cockpit video.) As already mentioned, configuration details are provided in Appendix B of Ref. 1.

Figure 2 shows example stick force time history and power spectral density (PSD) plots for the hookup and tracking tasks from one flight. From the time histories for configuration 2H, the input magnitude was significantly higher in the tracking task (30-s run length) than in the hookup task (10-s run length). For configuration 2D the input magnitudes were similar for both tasks.

The PSD plots reveal three significant results. First, the pilot was clearly able to perform closed-loop control at higher frequencies with configuration 2D (peak power at ≈6.5 rad/s) compared to 2H (peak power at ≈2–3 rad/s for the hookup task and 3–4 rad/s for the tracking task). Second, the frequency for peak input power varied by configuration, not by task. Third, the overall task gain is higher for both configurations in the tracking task as shown by the higher stick force input power at essentially all frequencies.

Analysis of Pilot B NT-33A Sortie

Data from the NT-33A sortie of Pilot B had several potential pitfalls. First, the evaluations were plagued by highly turbulent conditions that affected the ability of the pilot to successfully complete the tasks. In addition, problems with the digital data made it more difficult to reduce. Nevertheless, the results can still provide added insight into the hookup and tracking tasks and an interpilot comparison, so it has been included here.

The quantitative assessment included time and frequency domain analysis of longitudinal control force inputs of Pilot B. All three aircraft configurations (2D-Level 2 for hookup and Level 1 for tracking as evaluated by Pilot B, 2P-Level 1 for hookup and Level 2 for tracking as evaluated by Pilot B, and 2H-Level 3 for both tasks evaluated by Pilot B) were considered.

Figures 3 and 4 show example stick force time history and PSD plots for the hookup and tracking tasks, respectively. (The time scale is 10 s for the hookups and 30 s for tracking.) From the time histories it can be seen that for configuration 2D the pilot stick input magnitudes were similar for both tasks. Although the effects of the turbulence can be seen in two of the 2D hookup attempts, magnitudes are significantly lower overall when compared to the other two configurations. Several large end-game corrections are evident in the hookup task time histories for 2P. For configuration 2H the time histories indicate that the pilot had to significantly slow the stick input rate in comparison to 2D and 2P.

The PSD plots reveal several significant results. First, the pilot was clearly able to perform closed-loop control at higher frequencies with configuration 2D (peak power at ≈6.5 rad/s for the hookups and 8 rad/s for tracking) compared to 2P (peak power at ≈4.5 rad/s for both tasks) and 2H (peak power at ≈2.5–3 rad/s for the hookups and 3–3.5 rad/s for tracking). Second, the frequency for peak input power varied again by configuration, not by task. Third, the peak gain is higher for all configurations in the tracking task as shown by the higher stick force input power at the peak frequencies. This result is somewhat different from Pilot A (see Fig. 2) whose gain increased at essentially all frequencies for the tracking task. Both of these results do, however, indicate that more closed-loop control was required for the tracking task. Further comparisons show that Pilot B operated at significantly higher gain than Pilot A for the hookup task whereas their gains were similar for the tracking task.

Table 1 Recommended turbulence effect rating scale[6]

Increase of pilot effort with turbulence	Deterioration of task performance with turbulence	Rating
No significant increase	No significant deterioration	A
More effort required	No significant deterioration	B
	Minor	C
	Moderate	D
Best efforts required	Moderate	E
	Major (but evaluation tasks can still be accomplished)	F
	Large (some tasks cannot be performed)	G
Unable to perform tasks		H

Formal Demonstration Maneuver

The formal demonstration maneuver description for the resulting probe-and-drogue task, incorporating both tracking and hookups, is provided in Figs. 5 (Ref. 7) and 6.

Conclusions

The U.S. Navy-style probe-and-drogue maneuver proved to be a suitable handling qualities demonstration maneuver, provided it is flown as a combination task. Experience with task variations by students of the U.S. Air Force TPS provided an excellent method for refinement of the formal maneuver and exposed possible shortcomings as well. The HAVE GAS II test management project and corresponding data analysis produced the information necessary to define the final demonstration maneuver.

Pilot evaluations of three tasks flown in the HAVE GAS II project, and quantitative analysis of the flight data, clearly indicated that the drogue tracking task provided the better opportunity to evaluate closed-loop handling qualities. The drogue tracking task was, however, limited by the fact that it could not reveal potential problems that may be encountered within 5 ft of the basket. Thus it was concluded that a combination of the drogue tracking task and the hookup task should be flown to most thoroughly evaluate probe-and-drogue refueling handling qualities. When performed in concert, drogue tracking will provide the closed-loop evaluation whereas hookups will provide operational relevance and exposure to close-in effects near the basket.

A chase plane should be used to ensure that all evaluation pilots use the same distance from the probe to the basket when performing the drogue tracking task. The chase plane may be substituted for onboard sensors, for example, differential GPS, which can provide appropriate separation distances. Implementations of this type are currently in use at the U.S. Air Force Flight Test Center.

Finally, a rating scale that accounts for the effect of turbulence should be used.

Acknowledgments

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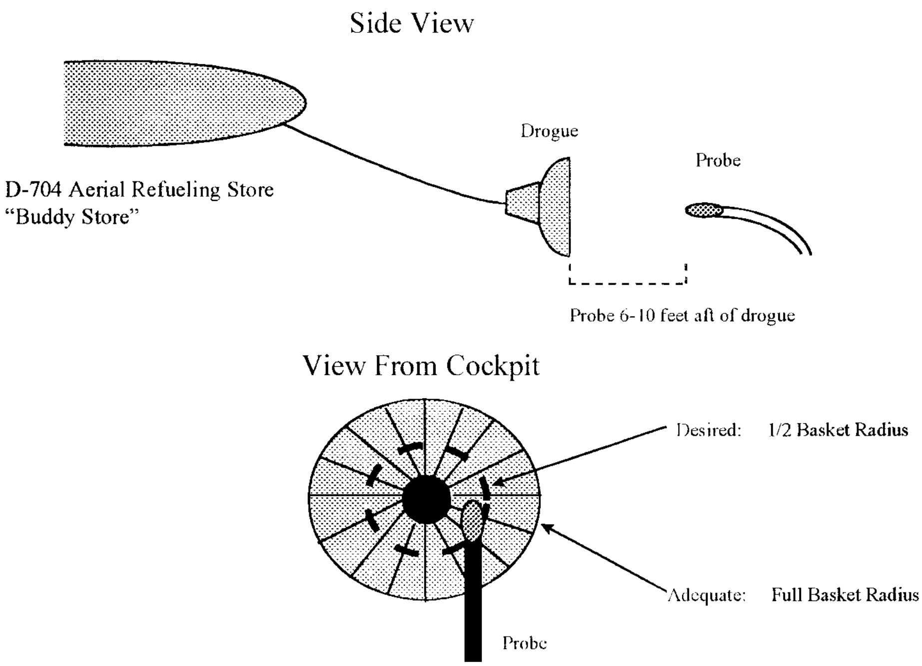

Fig. 6 Drogue tracking task geometry.[2]

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