JOURNAL OF GUIDANCE, CONTROL, AND DYNAMICS
Vol. 27, No. 1, January–February 2004

# Flight-Test Evaluation of Stability Augmentation Steering System for Aircraft Ground Handling

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**A flight-test program was conducted to evaluate a newly developed stability augmentation steering system (SASS). Designed to improve the ground-handling characteristics of a U.S. Navy jet trainer, the SASS features a yaw-rate feedback that is used to set the heading attitude bandwidth as desired, while providing an essentially constant rudder pedal sensitivity variation with speed. Flight-test efforts were conducted to assess performance of two SASS configurations against the baseline aircraft configuration. Three pilots evaluated the ability of the aircraft to perform a runway offset capture-and-hold maneuver, essentially a lane change task, with and without braking. The task with braking was found to be the better separator in terms of pilot ratings for the two SASS configurations when compared to the baseline aircraft. The flight-test program found that the SASS significantly improved the ground handling of the aircraft.**

## Nomenclature

| | | |
|---|---|---|
| $KDP$ | = | rudder pedal position gain |
| $KR$ | = | yaw rate feedback gain |
| $N_{ycg}$ | = | lateral acceleration at the center of gravity |
| $r$ | = | yaw rate |
| $\Delta\psi$ | = | heading deviation from runway centerline |
| $\delta_{NWS}$ | = | nose wheel steering position |
| $\delta_p$ | = | pedal position (also $\delta_{pedal}$) |

## Introduction

### Program Summary

A JOINT Boeing, Systems Technology, Inc. (STI), and U.S. Navy team has been working to assess and improve the ground-handling characteristics of a Navy jet trainer. The team initially worked together on a number of program tasks that included model development, ground-handling metric and maneuver development, and the evaluation of potential aircraft modifications. The use of a lower-order equivalent systems approach to determine the dominant ground handling characteristics of the aircraft is described in Ref. 1.

The baseline (unaugmented) aircraft is characterized by a heading attitude bandwidth that decreases with airspeed and reaches a minimum near 60 kn. This reduction in bandwidth results in an acceleration-command response type. Furthermore, the rudder pedal sensitivity variation with speed approaches its highest value, which is most sensitive when the heading attitude bandwidth approaches its lowest value, that is, most acceleration command-like.

It was found that just after touchdown the aircraft might be slightly understeer (i.e., the steady-state yaw rate gain is essentially constant with speed), but the understeer gradient decreases with speed, becoming oversteer (i.e., the steady state yaw rate gain varies significantly with speed and stability is reduced) at roughly 80 kn. From 80 to 40 kn the aircraft operates near the stability boundary, where the primary manual control problem is the lack of yaw-rate command bandwidth. The resulting ground-handling deficiencies are exemplified by the landing rollout pilot-induced oscillation (PIO) shown in Fig. 1. The PIO occurred as the pilot attempted an aggressive centerline crossing maneuver following a standard field landing.

Extensive use of piloted simulations was made to evaluate sensitivity to key parameters such as tire and landing gear strut characteristics, the effect of cockpit ergonomics on ground handling, and various stability augmentation schemes including the stability augmentation steering system (SASS) described in this paper.

### Heading Attitude Bandwidth

As described in Ref. 2, the primary ground-handling metric used in this program was heading attitude bandwidth. Key metric parameters include the bandwidth frequency, the neutral stability frequency, and phase delay (a measure of the high frequency phase roll off). The bandwidth parameters are obtained from an attitude to inceptor force response because the primary control cue for the pilot is attitude and not, for example, acceleration. In this way the higher-frequency effects of actuator and inceptor dynamics are also included. For ground handling the reference attitude is heading. Although no actual bandwidth/phase-delay requirements have been systematically defined for ground-handling applications, the success of the application of these parameters for pitch-and-roll attitude in flight suggests a similar sensitivity should exist in ground handling. From the series of piloted simulation studies described in Ref. 2, an excellent correlation with pilot ratings was obtained for the heading-attitude-bandwidth (HABW) metrics. In general, improvements in pilot opinion were seen with increasing bandwidth.

### Flight-Test Maneuvers

A ground-handling maneuver catalog was defined to cover the full range of piloted control including steady-state, transient, gross acquisition and tracking, and regulation tasks.[2] This coverage follows the mission-oriented approach, wherein an evaluation maneuver is defined for every mission task element that in this case was high-speed landing roll out. The resulting maneuvers successfully

Received 17 June 2003; presented as Paper 2003-5318 at the Atmospheric Flight Mechanics Conference, Austin, TX, 11 August 2003; revision received 20 August 2003; accepted for publication 20 August 2003. 

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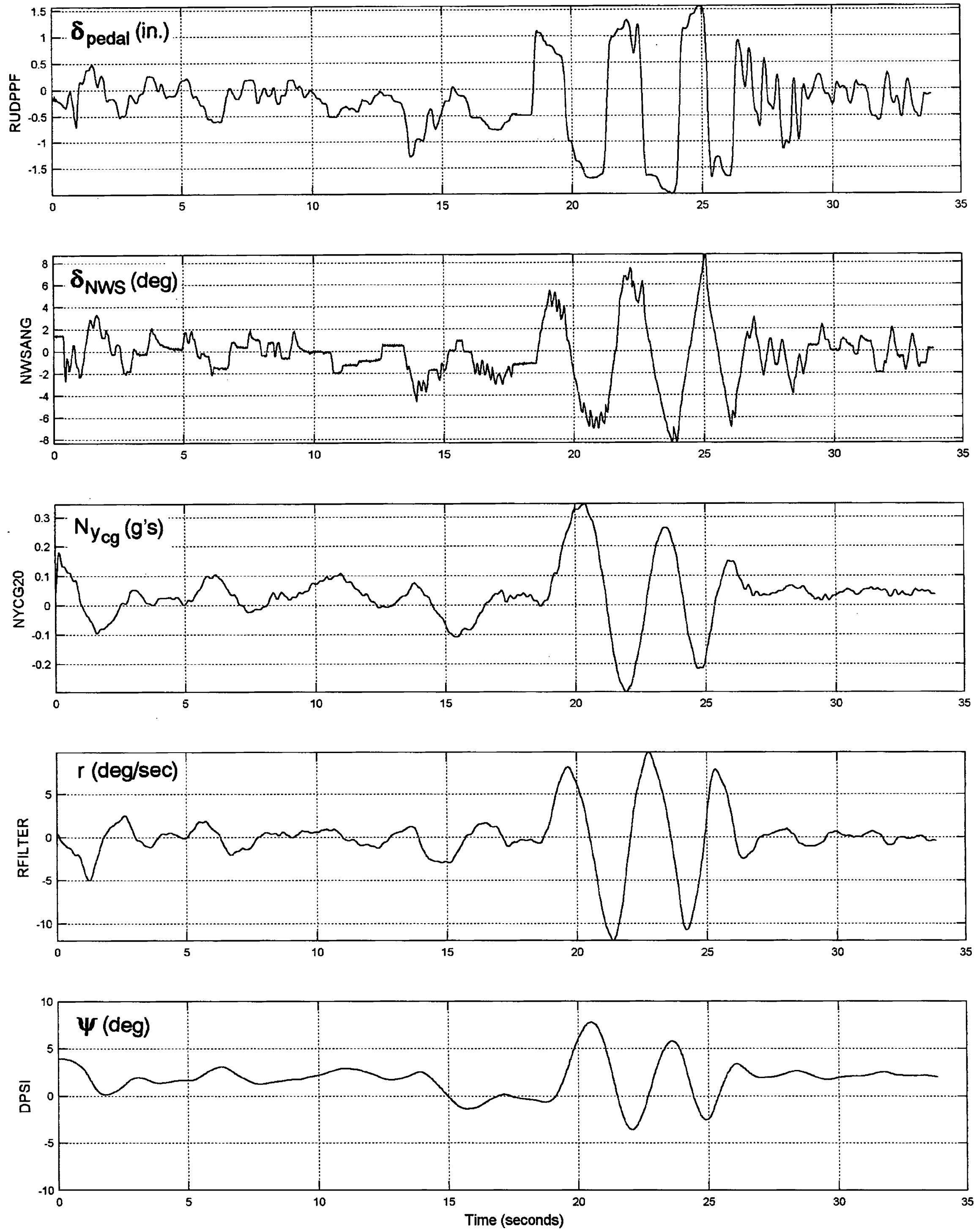



**Fig. 1 Example flight-test ground-handling PIO: high-speed landing roll-out centerline crossing task.**

uncovered pertinent ground-handling issues. Because of differing demands on the pilot and aircraft, no one maneuver was found to address all relevant issues. From this set three maneuvers were selected for use in the SASS flight-test evaluation.

### *Rudder Pedal Frequency Sweeps*

This diagnostic task was designed to identify aircraft frequency domain characteristics such as heading attitude bandwidth as a function of both aircraft configuration and flight condition. To perform the task, the pilot slowly increases the frequency of the rudder pedal input while maintaining input amplitude and speed essentially constant. Magnitude of the input can be increased over several runs at a given speed to better expose system nonlinearities. For ground-handling evaluations the frequency range of interest is generally from 0.1 to 10 rad/s. Because of runway length constraints, including those at Patuxent River Naval Air Station, the sweeps for a given configuration were conducted as a low-frequency run followed by a high-frequency run with repeats added as necessary.

### *Runway Offset Capture and Hold*

This task was designed to assess the ability of the aircraft to rapidly capture and maintain a new lateral position on the runway. To maintain a common level of aggressiveness, the range of the initial intercept angle shallows as speed increases (e.g., 5–7 deg at 50 kn, 4–6 deg at 75 kn, and 3–5 deg at 100 kn). For desired performance the pilot is required to capture the new runway position within ±2 ft and maintain this position for 5 s or until stable. Adequate performance for the capture and maintenance was ±5 ft. An initial overshoot within the performance requirements is allowed. Speed is held constant for a given evaluation. Because the handling qualities of a particular configuration can rarely be adequately assessed in a single event, the pilot is encouraged to continue with additional captures. Runway length constraints, including those at Patuxent River Naval Air Station, often require repeat evaluation runs before comments are given and ratings are assigned.

*Runway Offset Capture and Hold with Braking*

This gross acquisition and tracking task was designed to evaluate directional and lateral position dynamics in the presence of various levels of braking. In general, the directional characteristics of a vehicle are greatly influenced by braking in that braking forces reduce the ability of a tire to generate side force. The task is conducted in a manner similar to that already described for the runway offset capture and hold (ROCH); however, each capture is undertaken with a prescribed level of braking that in this case was a target deceleration of 0.15 $g$. The maneuver is initiated at 100 kn and is completed at 50 kn. The target intercept angle is 3–5 deg, and the desired and adequate performance requirements are the same as those for the ROCH. Of the three maneuvers, the ROCH and runway offset capture and hold with braking (ROCHB) maneuvers were assigned Cooper–Harper ratings.[3]

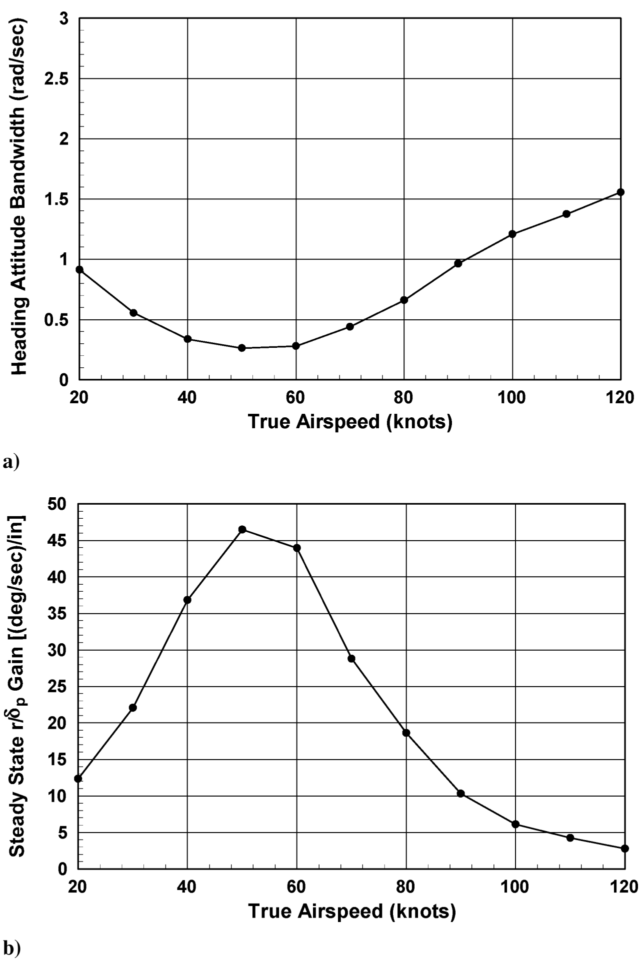



**Fig. 2 Open-loop vehicle characteristics as a function of airspeed.**

## Stability Augmentation Steering System

### Open-Loop Vehicle Description

Reference 1 gives a detailed description of the open-loop characteristics of the Navy trainer. Just after touchdown the aircraft might be slightly understeer, but the understeer gradient decreases with speed, becoming oversteer at roughly 80 kn. From roughly 80 to 40 kn, this variation is such that it remains close to the stability boundary. These characteristics are further explored in the open-loop heading attitude bandwidth and steady-state yaw-rate-to-rudder-pedal-sensitivity variations with airspeed shown in Fig. 2. These were identified from a linear lower-order equivalent systems model, enhanced to include a roll degree of freedom and aerodynamic effects. Hence, the heading attitude bandwidths displayed in the figure might be slightly different from those derived from flight-test data. Figure 2a indicates that heading attitude bandwidth decreases with airspeed and reaches a minimum near 60 kn. This reduction in bandwidth results in a more acceleration-command response type instead of the more desirable rate-command response type that is typically found with an understeer vehicle. Figure 2b illustrates the tremendous variation in rudder pedal sensitivity with speed. Note that this sensitivity approaches its highest value (i.e., most sensitive) when the heading attitude bandwidth approaches its lowest value (i.e., most acceleration command like).

### SASS Architecture

The SASS is a set of ground-handling control elements that provide yaw-rate feedback to nose wheel steering and adjustment of the rudder-pedal-to-nose wheel steering command sensitivity. The rudder pedal position gain *KDP* and the yaw-rate feedback gain *KR* as shown in Fig. 3 were modeled as functions of indicated airspeed to provide a constant heading attitude bandwidth. The indicated airspeed lower limit was set at 60 kn by performance of the airspeed sensor. This did not pose a problem, however, because the critical speed of the unaugmented aircraft—where stability augmentation is most needed—is very near 60 kn (see Fig. 2). The airspeed upper limit was set at 120 kn because high speed tends to reduce the vertical load on the nose wheel, thus reducing its control effectiveness. Furthermore, at these speeds directional stability is dominated by aerodynamic effects, and so additional stability augmentation is not required.

The "range of interest" of the yaw-rate feedback sensor is roughly ±25 deg/s for aircraft ground handling. This range would exceed expected maximum excursions from a blown tire, landing in a crab, crosswind gust response, differential brake response, or even a full pedal steering input at touchdown speed. In the SASS installation the yaw-rate signal is filtered to prevent structural mode interactions.

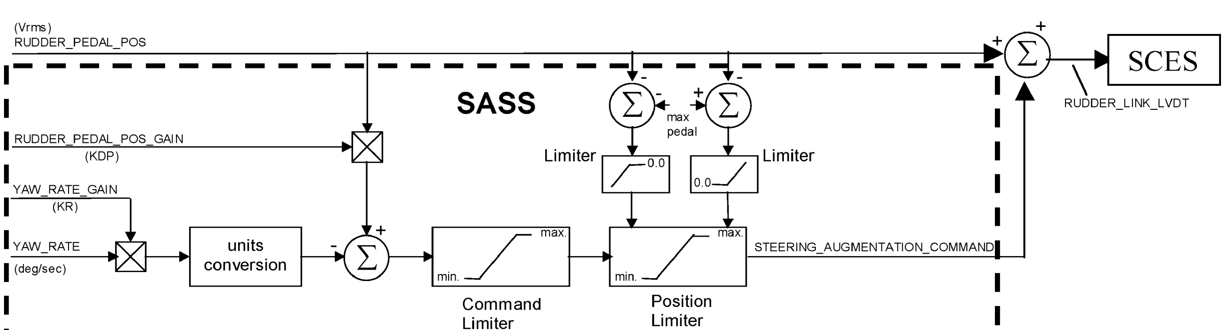



**Fig. 3 SASS block diagram.**

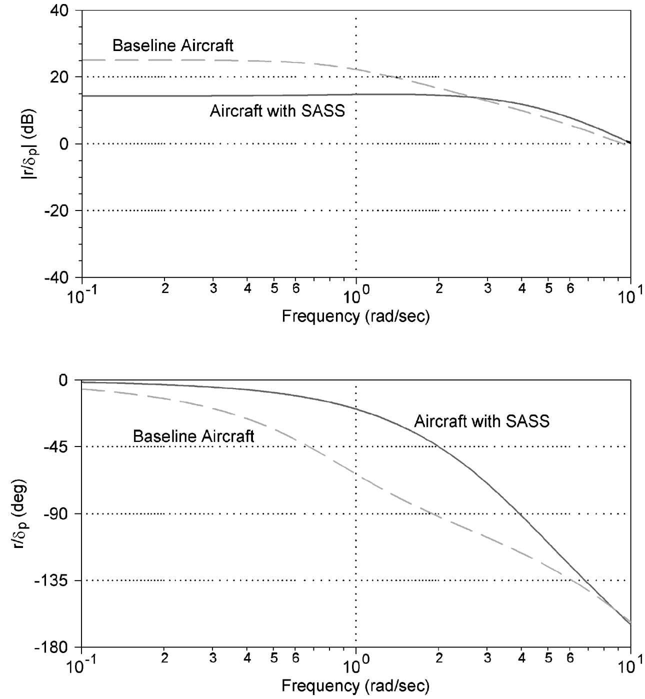



Fig. 4 Example SASS loop closure at 80 kn (SASS HABW = 2.0 rad/s).

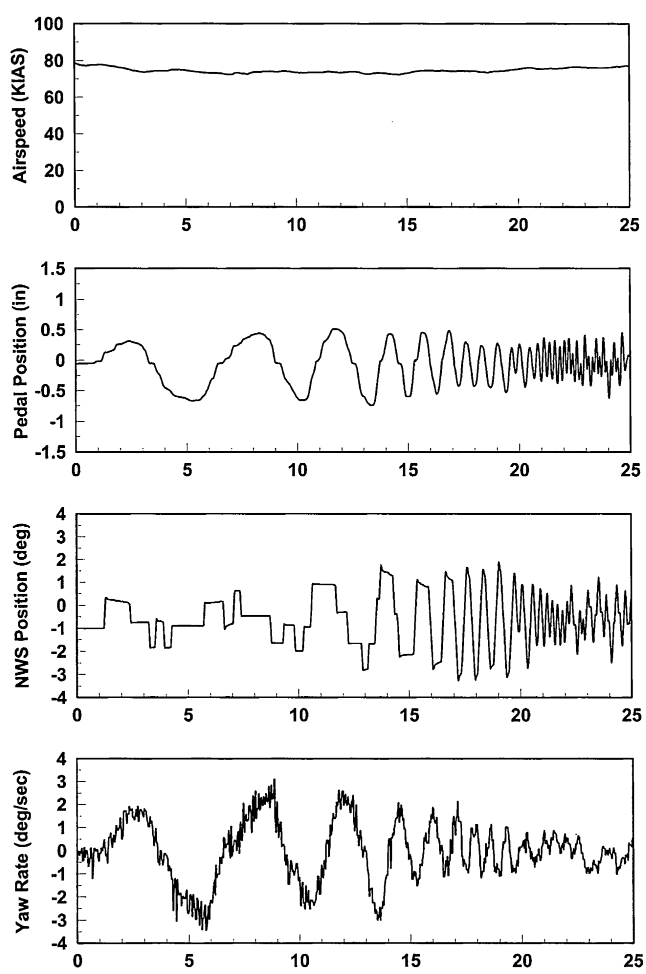



Fig. 5 Example rudder-pedal frequency sweep time history: 75 kn, SASS-2 configuration.

The SASS also features a command limiter and a position limiter. The command limiter was given full steering authority, ±12 deg of nose wheel steering. This high level of command authority was deemed necessary to dampen abrupt yaw rates that can occur during touchdown. The position limiter is required because the steering control electronic set (SCES) receives its steering input from a rudder-pedal linear voltage differential transducer (via a digital command). The SCES built-in test software continuously monitors this signal and will declare it failed if the expected range is exceeded. The position limiter therefore reduces the allowable SASS input that is in the same direction as the pedal input.

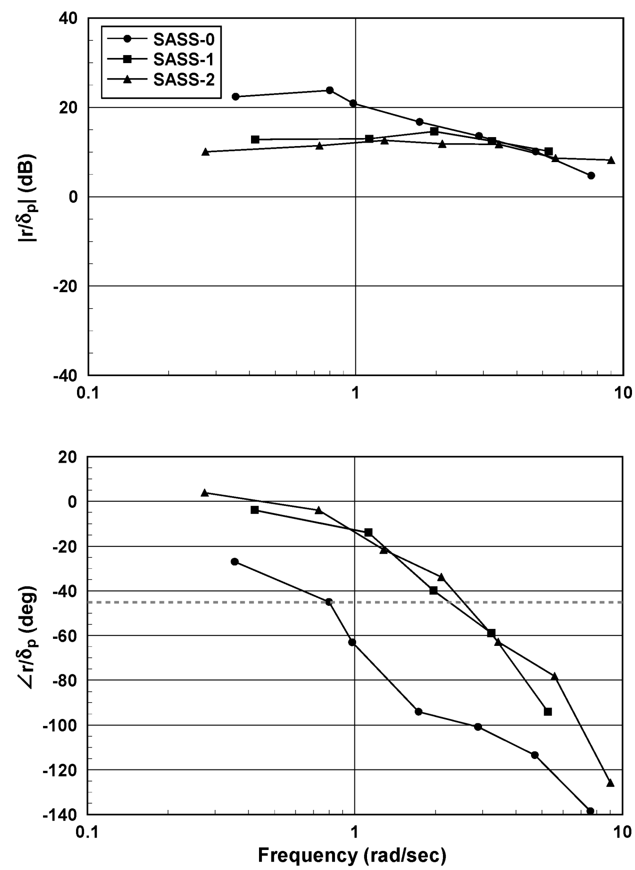



Fig. 6 SASS yaw-rate-to-rudder-pedal position $r/\delta_p$ frequency responses at 75 kn.

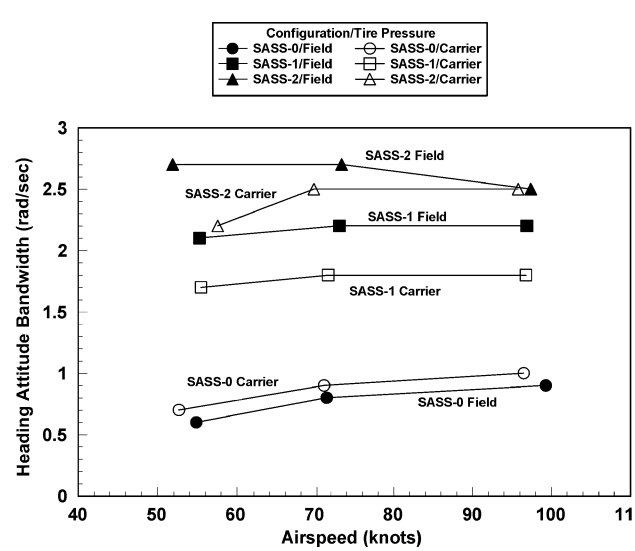
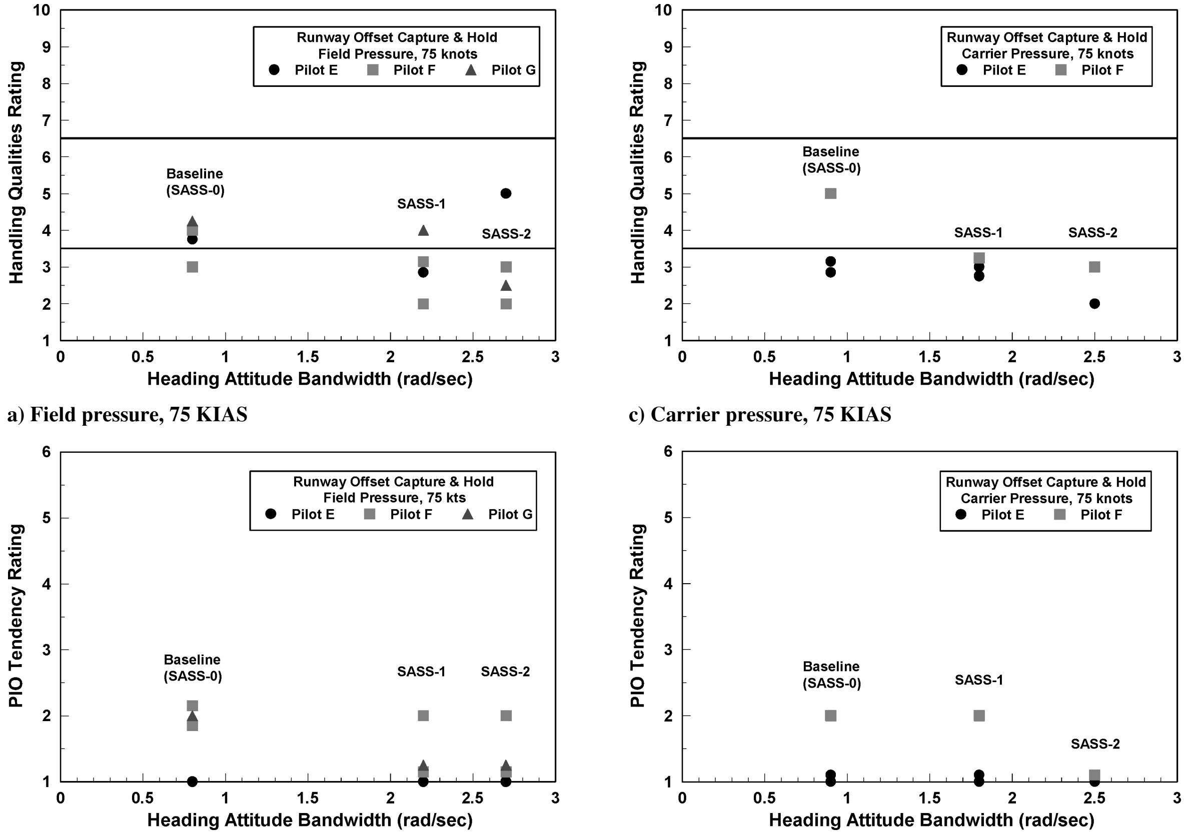



Fig. 7 Heading-attitude-bandwidth comparison of SASS configurations.



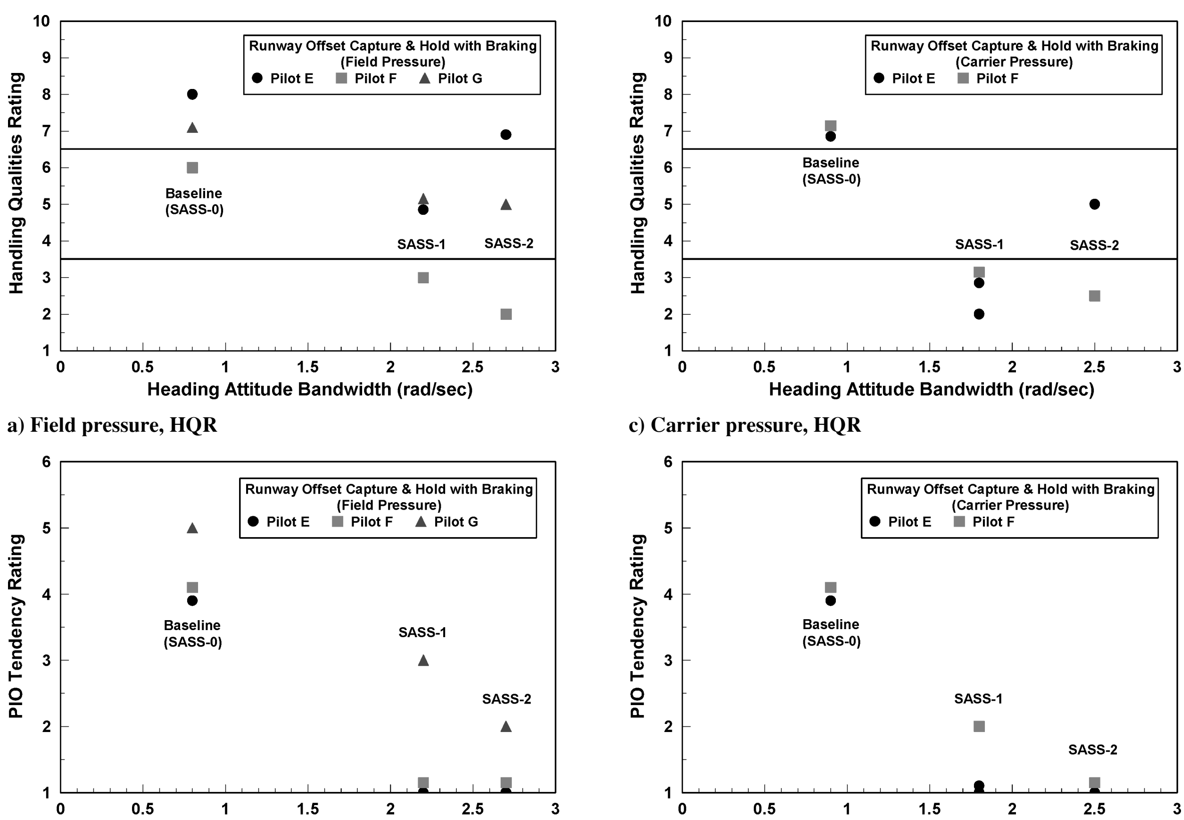

a) Field pressure, 75 KIAS

c) Carrier pressure, 75 KIAS

b) Field pressure, 75 KIAS

d) Carrier pressure, 75 KIAS

**Fig. 8 ROCH pilot ratings as a function heading attitude bandwidth.**




a) Field pressure, HQR

c) Carrier pressure, HQR

b) Field pressure, PIOR

d) Carrier pressure, PIOR

**Fig. 9 ROCHB pilot ratings as a function heading attitude bandwidth.**

**Closed-Loop System**

Figure 4 is a Bode plot comparing the unaugmented yaw rate to rudder-pedal response with that of the closed-loop system for an airspeed of 80 kn. In this example the yaw-rate feedback gain was tuned to provide a heading attitude bandwidth of 2.0 rad/s.

The reduction in the steady-state yaw-rate to rudder pedal sensitivity achieved with the SASS (25 dB for the unaugmented aircraft, 14 dB for the aircraft with SASS) is seen in the magnitude plot. When the yaw-rate feedback gain is scheduled with speed, the SASS steady-state sensitivity remains relatively constant across the speed regime of interest and thus achieves the desired understeer characteristic.[1] As just described, airplane bandwidth is ideally measured from an attitude Bode plot. If a rate rather than attitude Bode plot is available, the phase bandwidth frequency is simply identified from the −45-deg phase point rather than the −135-deg phase point. Thus, the phase plots of Fig. 4 indicate the improvement in heading attitude bandwidth that results from the SASS (2.0 rad/s for this SASS configuration and 0.65 rad/s for the unaugmented aircraft).

## Flight-Test Evaluation

**Overview**

Flights were conducted at the NAVAIR Naval Air Warfare Center Aircraft Division, Patuxent River, Maryland. Twenty-four flights were conducted from 16 May to 14 August 2002. Flights included rudder-pedal frequency sweeps and runway offset capture and hold

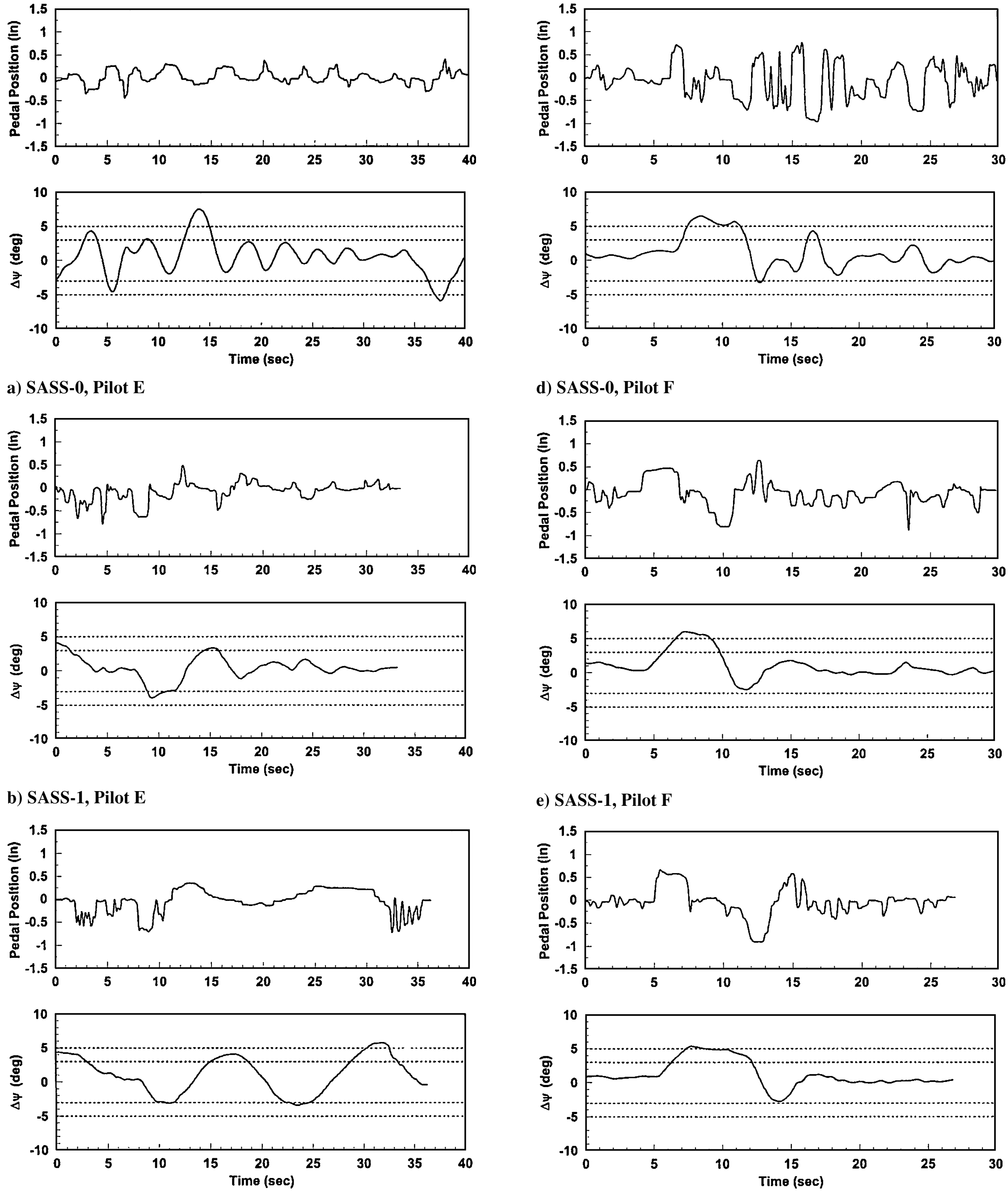


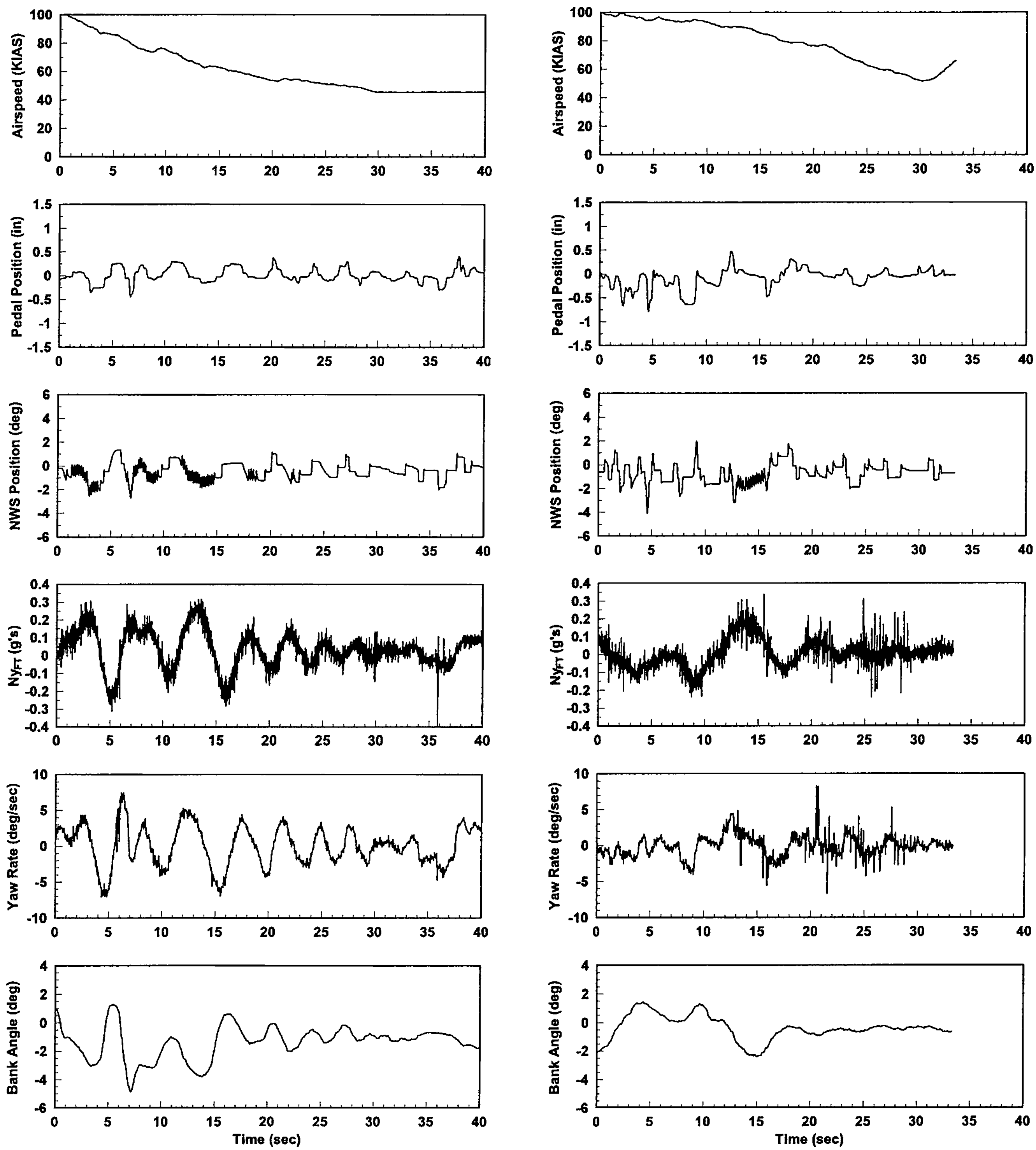

**Fig. 10 Heading attitude intercept angles for field pressure ROCHB evaluations.**

(with and without braking) tasks. Runway taxi tests and carrier deck handling "yellow-shirt" tests were also conducted but are not discussed in this paper. Frequency sweeps and ROCH evaluations were conducted at speeds of 50, 75, and 100 kn, whereas ROCHB evaluations were conducted from 100 to 50 kn.

Three test pilots from Air Test and Evaluation Squadron (VX-23) participated in the program and are referred to as pilots E, F, and G. (Pilots A–D participated in the earlier phases of the program described in Refs. 1, 2, 4.) Three SASS configurations were evaluated: SASS-0—baseline aircraft; SASS-1—HABW $\approx$ 2.0 rad/s; and SASS-2—HABW $\approx$ 2.5 rad/s. Evaluations were conducted for two aircraft configurations: field service (125 psi tires) and carrier service (350 psi tires).

**Rudder-Pedal Frequency Sweeps**

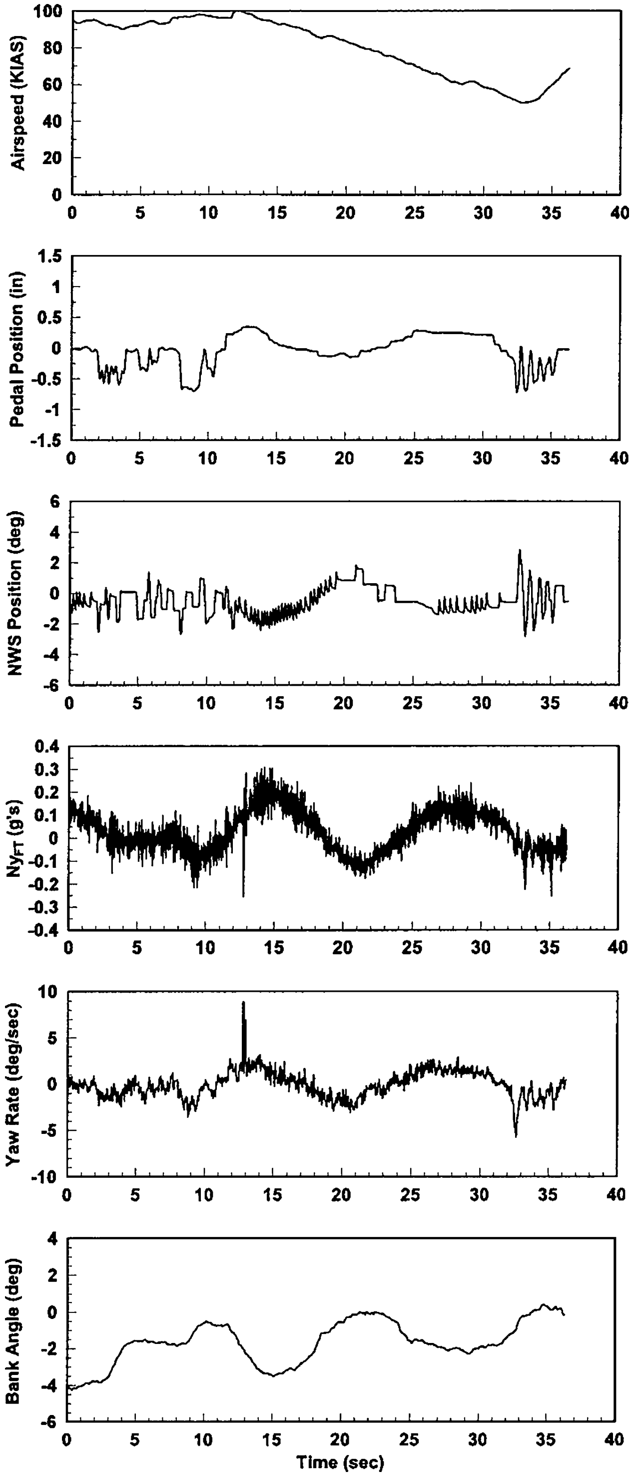
Figure 5 presents a rudder-pedal sweep time history for the higher frequency portion of a 75-kn test point. (Because of runway length considerations, the higher-speed test points were broken into high-frequency and low-frequency runs.) The strip chart plots show the aircraft airspeed, rudder-pedal position, nose wheel steering angle, and yaw rate. These parameters were used to identify the directional response of the aircraft $r/\delta_{\mathrm{NWS}}$, the nose wheel actuator $\delta_{\mathrm{NWS}}/\delta_p$,




a) SASS-0, HQR 8/PIOR 4

b) SASS-1, HQR 5/PIOR 1

**Fig. 11 Time histories for pilot E ROCHB evaluations.**



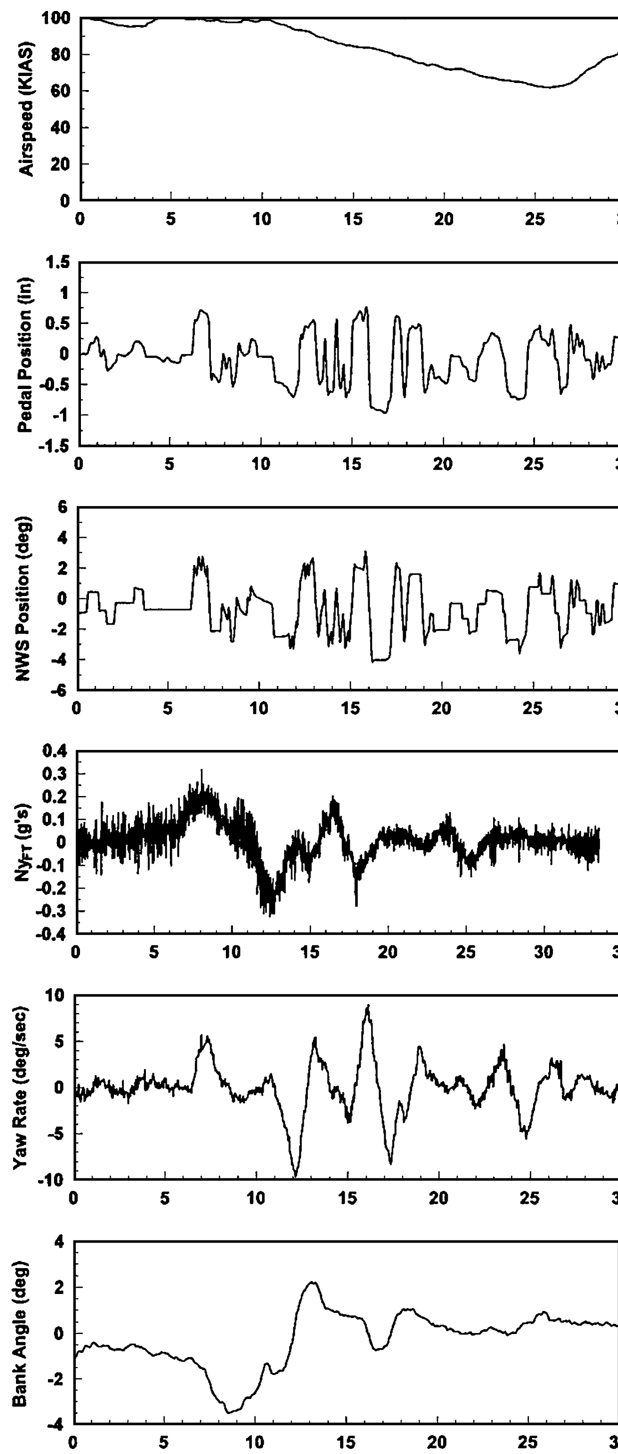

c) SASS-2, HQR 7/PIOR 1

**Fig. 11 Time histories for pilot E ROCHB evaluations (continued).**

and the aircraft plus actuator, $r/\delta_p$. The analysis presented herein focuses on the aircraft plus actuator $r/\delta_p$ response, used to determine the heading-attitude-bandwidth parameters.

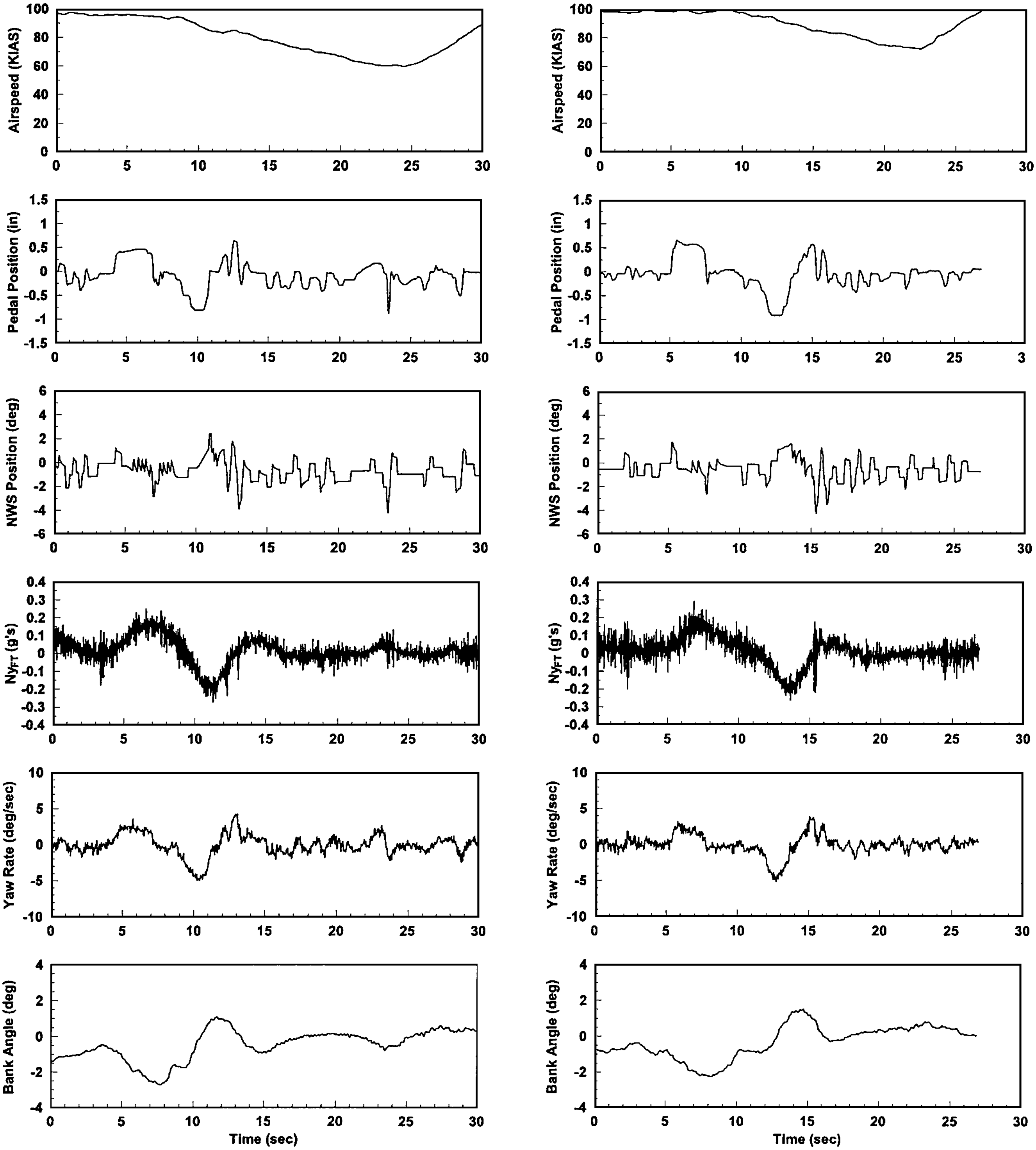
A specialized fast Fourier transform (FFT) software package developed by STI (FREDA, Frequency Domain Analysis) was used to compute the yaw-rate-to-rudder-pedal frequency responses from the rudder-pedal frequency sweep time histories. Data from runs for a given speed and SASS configuration were combined to produce one "long run" that maximized the data used in the FFT to calculate the heading-attitude-bandwidth parameters for each configuration. The identification of this parameter from the field service pressure frequency responses at 75 kn is illustrated in Fig. 6 for all three SASS configurations by the intersection of the phase Bode with the −45-deg line. Only high coherence data (i.e., $\rho^2 > 0.65$) were used. Figure 6 clearly demonstrates the improvement in heading attitude bandwidth achieved with the augmented configurations. Flight tests revealed the achieved bandwidths to be slightly higher than the predicted design values (2.2 rad/s vs 2.0 rad/s for SASS-1 configuration and 2.7 rad/s vs 2.5 rad/s for SASS-2 configuration).

The frequency sweep data were used to compare the SASS configuration heading attitude bandwidths with the baseline aircraft for both field and carrier service tire configurations as shown in Fig. 7. From this plot the significant improvement in heading attitude




a) SASS-0, HQR 6/PIOR 4

**Fig. 12 Time histories for pilot F ROCHB evaluations.**




**b) SASS-1, HQR 3/PIOR 1** **c) SASS-2, HQR 2/PIOR 1**

**Fig. 12 Time histories for pilot F ROCHB evaluations (continued).**

bandwidth for the SASS-1 and SASS-2 configurations is clearly revealed. This improvement is observed across the airspeed range. As already mentioned, the actual bandwidths for the SASS-1 and SASS-2 configurations in the field service configuration were slightly higher than the predicted design values. As expected, the carrier service augmented bandwidths were slightly reduced from the respective field service (augmented) configurations.

Results for the baseline aircraft in the field service configuration match those derived from previous flight tests (Ref. 4). The bandwidths of the baseline configuration with carrier service configuration were noted to be slightly higher than the field service configuration because of the reduced cornering capability of the high-pressure nose tires (350 psi vs. 125 psi).

### ROCH Evaluations

During initial flight-test efforts, ROCH evaluations were conducted for a given SASS configuration at all three speeds before proceeding to the next configuration. Following these flights, it was decided that better comparisons between configurations could be obtained by completing all ROCH evaluations (baseline aircraft, SASS-1, and SASS-2) at a given speed before proceeding to the next speed. The remaining evaluations as well as a repeat of the

75-kn ROCH evaluation by pilot F were completed in this manner. Pilot G conducted ROCH and ROCHB evaluations in the field service configuration only.

A summary of the ROCH evaluation ratings assigned by all three pilots for the 75-kn test point is presented in Fig. 8. Although comments from pilots E and F clearly favor the augmented configurations, significant ratings differences are not evident for this task. This might be caused in part by the familiarity of the pilots with the unaugmented aircraft. For example, pilot F referred to the baseline configuration as "unpredictable, with an apparent lag in response that felt much like an acceleration-command system," yet was still able to achieve desired performance. In contrast, he referred to SASS-1 as being "very predictable. Good balance between sensitivity and authority. Damping much better than SASS-0 (baseline configuration), but not as good as SASS-2." He found SASS-2 to be "very predictable but sluggish. Much larger pedal inputs required."

Comments from pilot E were similar to those of Pilot F, but clearly favor SASS-1: "SASS positions 1 and 2 both offered deadbeat response to directional control inputs however SASS position 1 was more responsive and therefore felt more predictable and was preferred over SASS position 2." The ratings of pilot G follow the trends of the other pilots. With the carrier service pressure tires pilots E and F assigned level 1 ratings to the SASS-1 and SASS-2 configurations at all speeds. As shown in Fig. 8, no PIO tendencies were noted with any of the configurations.

**ROCHB Evaluations**

*Pilot Rating Summary*

ROCHB maneuvers were flown and evaluated by pilots E and F in both field and carrier service configurations, whereas pilot G flew and evaluated the field service configuration only. The handling-qualities ratings and PIO-tendency ratings for this task are shown in Fig. 9 as a function of heading attitude bandwidth. As speed varies in this maneuver from 100 to 50 kn, bandwidths at the median value of 75 kn were used to create the plots. In contrast to the ROCH task, the demands of this combined braking and cornering maneuver provided a larger separation in pilot ratings between the configurations. Specifically, the ground-handling deficiencies and PIO tendencies of the baseline configuration were clearly evident and were reflected in the level 3 handling qualities ratings and PIO ratings of 4 and higher.

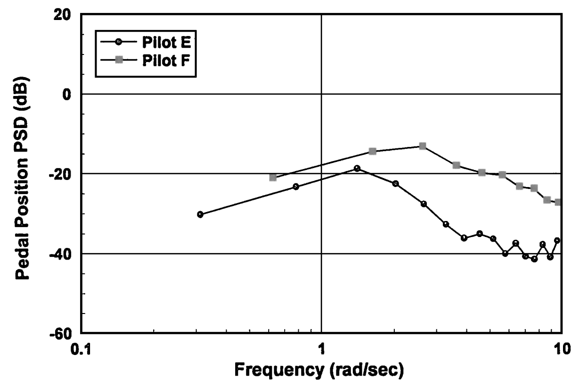
In describing this configuration, pilot E noted that "considerable compensation was required (continual directional inputs of approximately 1" at about 2 Hz frequency) in order to maintain control during the task and the resultant oscillations required the pilot to abandon the task." In terms of PIO, neither pilot E nor F noted any PIO tendencies in either augmented configuration. Pilot G, on the other hand, indicated via a PIO rating of three that undesirable motions affected task performance with the SASS-1 configuration. This might be a learning-curve artifact, however, because this evaluation followed his first attempts at the task. From a ratings only point of view, SASS-1 was the best performer. Pilot E felt that "clearly the SASS positions 1 and 2 are better and SASS 1 offered a more predictable response with less lag and overshoot potential when compared to SASS 2." Pilot F preferred the damping characteristics of SASS-2, but the control authority (i.e., rudder-pedal sensitivity) of SASS-1. He gave both configurations level 1 ratings.

*Quantitative Analysis*

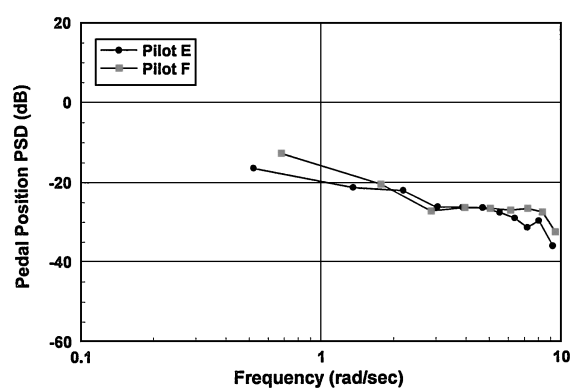
Figure 10 shows time-series plots of the pilots' rudder-pedal inputs and the resulting intercept angles for the field service pressure ROCHB evaluations. The maneuver description requires the intercept angle to fall between 3 and 5 deg, indicated by the dotted lines on the $\Delta\psi$ plots. In reviewing the pilot E time histories for the baseline SASS-0 configuration, a classic PIO was observed (i.e., the heading response is 180 deg out of phase with the rudder pedal position for nearly 25 s). Pilot E was only able to meet the performance requirements for the maneuver with the SASS-1 configuration, and here the intercept angle was within the desired range though on the shallow side. Examining the pedal response, it is clear that the task was abandoned with the SASS-2 configuration. The pilot noted that "the large lag associated with SASS position 2 resulted in overshoots and I was unable to obtain adequate performance although the motion was deadbeat." In contrast, pilot F slightly exceeded the intercept angle range for the baseline while SASS-1 was on the high side of the SASS-2 case. The larger intercept angles result in more aggressive lane position captures.

Figures 11 and 12 present a set of time histories for pilot E and pilot F ROCHB evaluation runs. Each time-history set includes airspeed, rudder pedal position, nose wheel steering position, lateral acceleration, yaw rate, and bank angle. As mentioned earlier, pilot E was able to successfully complete the task only in SASS-1 configuration, a result that is clearly reflected in his ratings. Furthermore, the sustained oscillations of the PIO are evident in all of the key aircraft response variables for the baseline configuration.

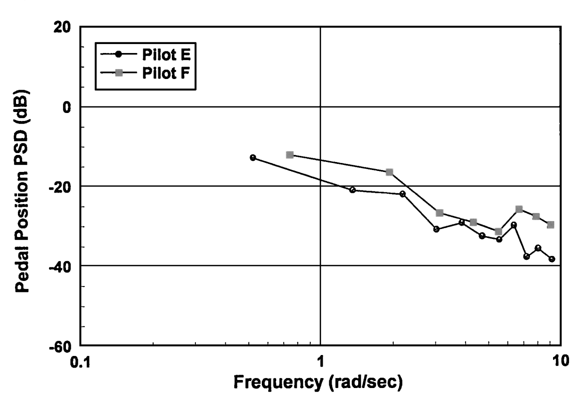
Although pilot F was able to complete the task in all three configurations, the deficiencies of the baseline configuration are noted in the time traces, notably the significantly higher peak yaw rates. These results indicate that the ROCHB task exposed the handling-qualities cliff that was known to be present with the baseline aircraft. Expectedly, the nearly identical responses of the SASS-1 and SASS-2 runs




a) SASS-0




b) SASS-1




c) SASS-2

**Fig. 13 Rudder-pedal position power spectra density plots for ROCHB evaluations.**

of Pilot F yielded similar ratings, although preference for SASS-2 was indicated.

Power spectral density (PSD) plots of the rudder pedal position signal were generated for the ROCHB evaluations as well. The results are shown in Fig. 13 for each configuration. The baseline configuration reveals clear differences between pilot E and F input PSD. Because pilot E entered a PIO as the maneuver began, his input power shows a peak near the PIO frequency. Pilot F maintains higher gain at frequencies beyond 2 radians/s to successfully complete the task.

For the SASS-1 configuration the resulting PSDs are nearly identical. For the SASS-2 configuration pilot F was again comfortable in using the increased inputs required to perform the task, whereas Pilot E was not.

## Conclusions

A flight-test program was conducted to evaluate the performance of a stability augmentation system in improving the ground handling characteristics for a Navy jet trainer. Qualitative and quantitative ratings from three pilots (pilots E, F, G) were used to measure the improvement of two augmented configurations over the baseline aircraft. The results of the formal evaluations, consisting of ROCH and ROCHB runs, indicated that both augmented configurations (SASS-1 and SASS-2) were strongly favored over the baseline configuration by all three pilots. Pilot E clearly favored the SASS-1 configuration for achieving desired task performance for all but one evaluation. While finding the stability of SASS-2 to be significantly improved over the baseline, pilot E indicated that the pedal forces required to accomplish the tasks were excessive. Pilot F, on the other hand, achieved desired task performance with level 1 ratings for all evaluations with both SASS configurations, but favoring the SASS-2 configuration. Pilot F liked the damping of SASS-2, but the pedal sensitivity of SASS-1. Pilot G preferred both augmented configurations over the baseline, but no clear favorite is discernable from the ratings alone. (Time series data and written pilot comments were not available for pilot G's evaluations at the time this paper was written.) Using the PIO-tendency ratings for the ROCHB task, however, Pilot G found SASS-2 more resistant to undesirable motions when compared to SASS-1. The reader should be cautious in placing too much emphasis on this difference, however, because this difficult task was performed first with the SASS-1 configuration and was rated after only one attempt.

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