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Effect of Tire Pressure on Aircraft Ground Handling

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Handling of ground vehicles is dominated by the ability of the tires to generate cornering and braking forces. Tire forces are a function of the contact patch slip angle, the longitudinal slip ratio, normal load, and inflation pressure. Comprehensive tire tests were conducted as part of a program to assess the ground handling of a Navy trainer. The results indicated that improvements may be seen by setting the nose tire pressure to the higher carrier service pressure, while the main gear tires remain at field service pressure. To test for such an improvement, a ground handling flight test program was undertaken. Rudder pedal frequency sweeps were used to determine heading attitude bandwidth parameters, and a runway offset capture and hold maneuver was used to generate pilot handling qualities assessments. The frequency sweep data indicated an improvement in heading attitude bandwidth for the new configuration. The ratings of one pilot indicated a one- to two-point improvement with the new configuration. The ratings of the second pilot did not vary significantly between configurations; however, his comments indicated a clear preference for the new configuration. It was demonstrated through time history comparisons that the differences between the two evaluation pilots resulted primarily from pilot technique.

Nomenclature

a	=	distance from center of gravity to nose gear tire
b	=	distance from center of gravity to main gear tire
F_{pedal}	=	rudder pedal force
F_z	=	tire normal force
g	=	gravity constant
K	=	stability factor
m	=	aircraft mass
p	=	tire pressure
R	=	effective loaded tire radius
r	=	yaw rate
S	=	tire longitudinal slip ratio
U_c	=	critical speed
U_0	=	aircraft forward speed
u	=	wheel hub velocity
Y_{α_1}	=	tire cornering coefficient for nose gear
Y_{α_2}	=	tire cornering coefficient for main gear
α	=	tire slip angle
$\Delta\psi$	=	heading intercept angle for runway offset capture and hold task
δ_{NWS}	=	nose wheel steering deflection
δ_p	=	rudder pedal deflection
δ_w	=	nose wheel angle
μ_α	=	normalized tire cornering coefficient
τ_p	=	bandwidth phase delay
ψ	=	heading attitude
ω	=	wheel angular velocity
ω_{BW}	=	bandwidth frequency
ω_{180}	=	neutral stability frequency

Introduction

SYSTEMS Technology, Inc. (STI), was contracted to perform an assessment of the ground handling of a U.S. Navy jet trainer. STI worked with The Boeing Company and the U.S. Navy on a number of program tasks that included linear modeling, ground-handling metric and maneuver development, and evaluation of potential aircraft modifications. Previous papers identified the dominant ground-handling characteristics using a lower-order equivalent systems modeling approach[1] and described the development and evaluation of ground-handling maneuvers and metrics.[2] As described in Ref. 1, it was found that just after touchdown the aircraft may be slightly understeer, that is, the steady-state yaw rate gain is essentially constant with speed, but the understeer gradient decreases with speed, becoming oversteer, that is, the steady-state yaw rate gain varies significantly with speed and stability is reduced, at roughly 80 kn. From roughly 80 to 40 kn, this variation is such that it remains close to the stability boundary. Aerodynamic forces provide a significant stabilizing effect at higher speeds. Thus, in the 80–40 kn region where the aircraft operates near the stability boundary, controllability as measured by yaw rate command bandwidth is the primary manual control problem, not instability per se.

In Ref. 2, the 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. 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 rollout and included the compounding effects of braking, crosswinds, and blown tires. The resulting maneuvers successfully uncovered pertinent ground-handling issues. Because of differing demands on the pilot and aircraft, no one maneuver was found to address all relevant issues. In a parallel activity, candidate ground-handling metrics were defined using the long history of aircraft flying qualities and ground-vehicle-handling work. These included understeer gradient, heading attitude bandwidth, transient response characteristics, and closed-loop pilot–vehicle system measures. The ground-handling metric that was found to be most applicable, selective, traceable, readily obtainable, and reproducible was heading attitude bandwidth. Given a more extensive ground-handling flight-test database, this metric could be easily transitioned to a design criterion.

As part of the ongoing work concerning the ground handling of the U.S. Navy trainer, comprehensive tire testing was conducted on a set of nose and main gear tires. The testing featured cornering and

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braking runs at both field and carrier tire pressures. The results of this testing indicated that improvements in ground handling may be seen by setting the nose tire pressure to the higher carrier service pressure, while the main gear tires remained at the lower field service pressure. This paper presents the results of a flight-test program that was undertaken to evaluate the ground handling of the aircraft with high-pressure nose tires.

Background

Tire Characteristics

Aircraft tire side (cornering) and longitudinal (braking) forces are primarily functions of four variables: slip angle α, longitudinal slip ratio S, normal load F_z, and inflation pressure p (Ref. 3). The derivative of tire side force with respect to slip angle defines the very important tire cornering stiffness Y_α, as shown in Fig. 1. In general, the cornering stiffness of automobile tires when normalized by normal load μ_α decreases as normal load increases.[4] This behavior is also evident in the main gear tire data presented in Fig. 1 and for the nose gear tire data as well. Longitudinal slip S occurs in braking when the product of wheel angular velocity ω and the effective loaded tire radius R is less than the hub velocity u. As exemplified by the main gear tire data, longitudinal slip reduces the cornering stiffness in braking, which, thus, reduces the stability factor or understeer gradient.

The static and dynamic stability of ground vehicles is routinely expressed in terms of either stability factor K (in seconds squared per square foot) or understeer gradient (UG) (in degrees per gravity acceleration) that are readily developed from the two-degree-of-freedom ground vehicle model.[1] These two parameters are closely related and are routinely used interchangeably:

$$K = \frac{m\left(bY_{\alpha_2} - aY_{\alpha_1}\right)}{2(a+b)^2 Y_{\alpha_2} Y_{\alpha_1}}, \qquad \mathrm{UG} = 57.3g(a+b)K$$

The parameters m, a, b, Y_{α_1}, and Y_{α_2} are as defined in Ref. 1. These parameters arise from the steady-state yaw rate to steering command gain $G^r_{\delta_w}(0)$ (per second) as given by

$$G^r_{\delta_w}(0) = U_0/(a+b)\left(1 + KU_0^2\right)$$

When $K = 0$, the vehicle is said to be neutral steer and the yaw rate gain increases in proportion to speed. In contrast, when $K > 0$, the vehicle is understeer, and the yaw rate gain tends to be more constant with speed. Through long experience with automobile handling, it has been found that the understeer characteristic is most appropriate for most passenger cars and ordinary drivers. Finally, when $K < 0$, the vehicle is oversteer. Above the critical speed U_c,

$$U_c = 1\big/\sqrt{-K}$$

the vehicle becomes directionally unstable. The oversteer characteristic is generally considered an inappropriate handling characteristic for ordinary drivers, although racing cars are sometimes setup to be oversteer for increased agility.

Heading Attitude Bandwidth

The airplane bandwidth criterion was developed from the crossover model concept.[5] As described in Ref. 6, the attitude bandwidth is related to the premise that the maximum crossover frequency that a pure gain pilot can achieve, without threatening stability, is a valid figure of merit for the controlled element. Key bandwidth parameters include the bandwidth frequency ω_{BW}, the neutral stability frequency ω_{180}, and phase delay, a measure of the high-frequency phase rolloff τ_p. As shown in Fig. 2 (from Ref. 7) 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 included. For ground handling, the reference attitude is heading. Although no actual bandwidth/phase delay requirements have been defined for

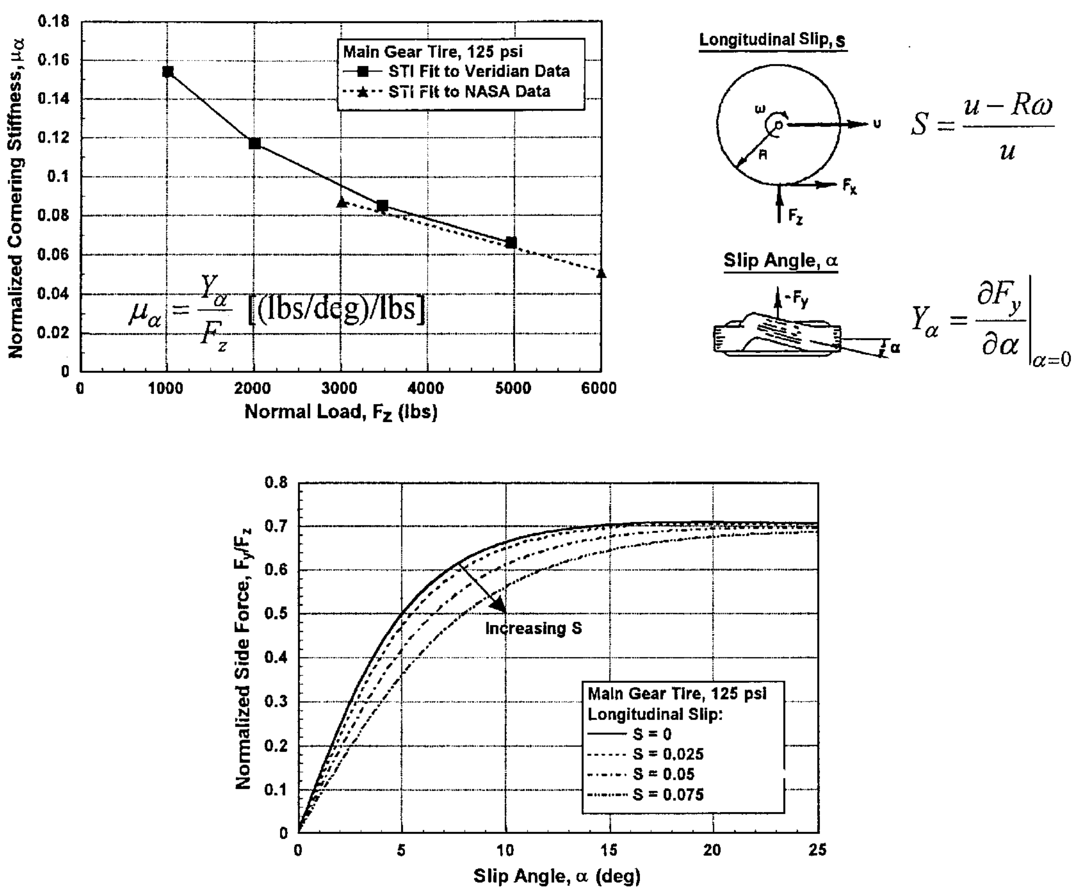


Fig. 1 Example aircraft main gear tire characteristics.

ground handling, the results discussed in Ref. 2 indicate that heading attitude bandwidth was an applicable, selective, traceable, readily obtainable, and reproducible ground-handling metric. Given a more extensive ground-handling flight-test database, this metric could be easily transitioned to a design criterion.

Ground-Handling Maneuvers

Of the 10 candidate ground handling tasks described in Ref. 2, perhaps the one with the most operational relevance is the runway offset capture and hold (ROCH). This task is designed to assess the ability of the aircraft to rapidly capture and maintain a new lateral position on the runway. An illustration is provided in Fig. 3. Following the format established in Ref. 8, the task definition includes a list of objectives, a description, and desired and adequate performance requirements, as follows:

Objectives

1) Evaluate ability to maneuver and capture a new runway lateral position.

2) Identify maneuverability limitations and PIO tendencies.

Description

Begin the maneuver from a steady ground roll along the runway centerline. Rapidly capture a runway reference line that parallels the centerline (≈ 40-ft offset) and maintain within the specified tolerances for 5 s or until stable (runway "tar lines" provide useful references). Then perform subsequent captures back to the centerline, left of the centerline, etc., until you are ready to rate the configuration. Use additional runs if necessary. Before proceeding to the next capture, maintain each heading within the specified tolerances for 5 s or until stable. The task should be attempted at a series of ground speeds from the nominal landing speed to 50 kn, with minimal, steady, and fluctuating crosswinds. The initial intercept angle for each capture should be 5–7 deg at 50 kn, 4–6 deg at 75 kn, and 3–5 deg at 100 kn.

Desired Performance

1) Capture and hold ±2 ft of the target offset.

2) Magnitude of the initial overshoot remains within the desired offset region.

Adequate Performance

1) Capture and hold ±5 ft of the target offset.

2) Magnitude of the initial overshoot remains within the adequate offset region.

Figure 3 provides a visual interpretation of the capture and hold performance requirements. Because the handling qualities of a

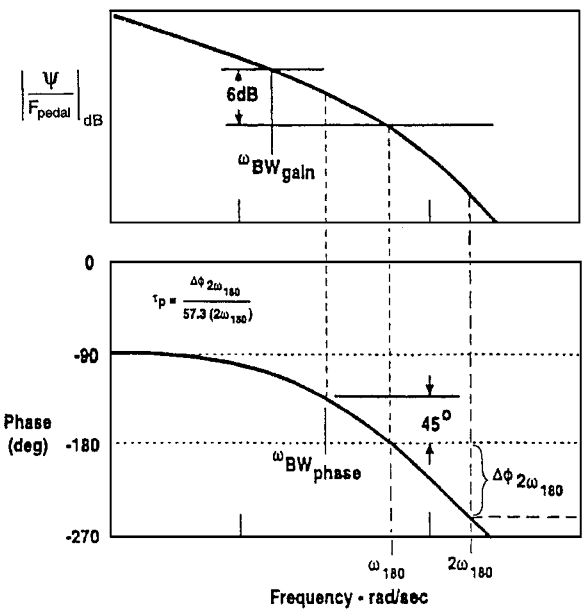


Fig. 2 Airplane heading attitude bandwidth parameter definitions (from Ref. 7) rate response types are ω_{BW} is lesser of $\omega_{BW_{gain}}$ and $\omega_{BW_{phase}}$, and attitude response types are $\omega_{BW} = \omega_{BW_{phase}}$.

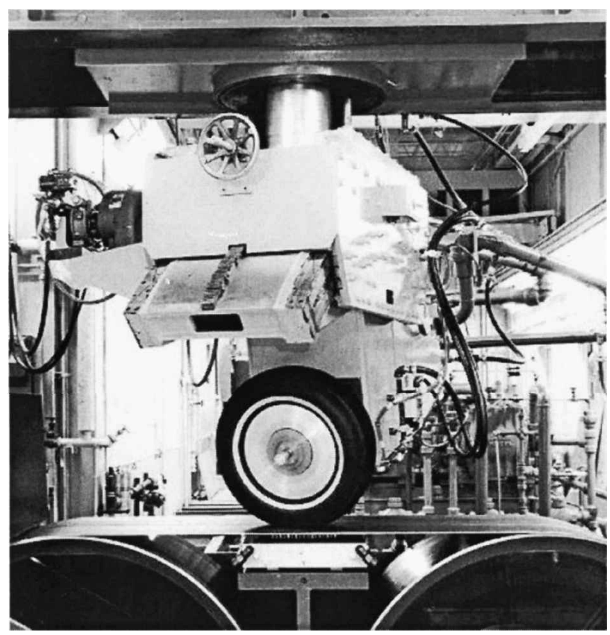


Fig. 4 Veridian tire test facility (photograph from Veridian Engineering).

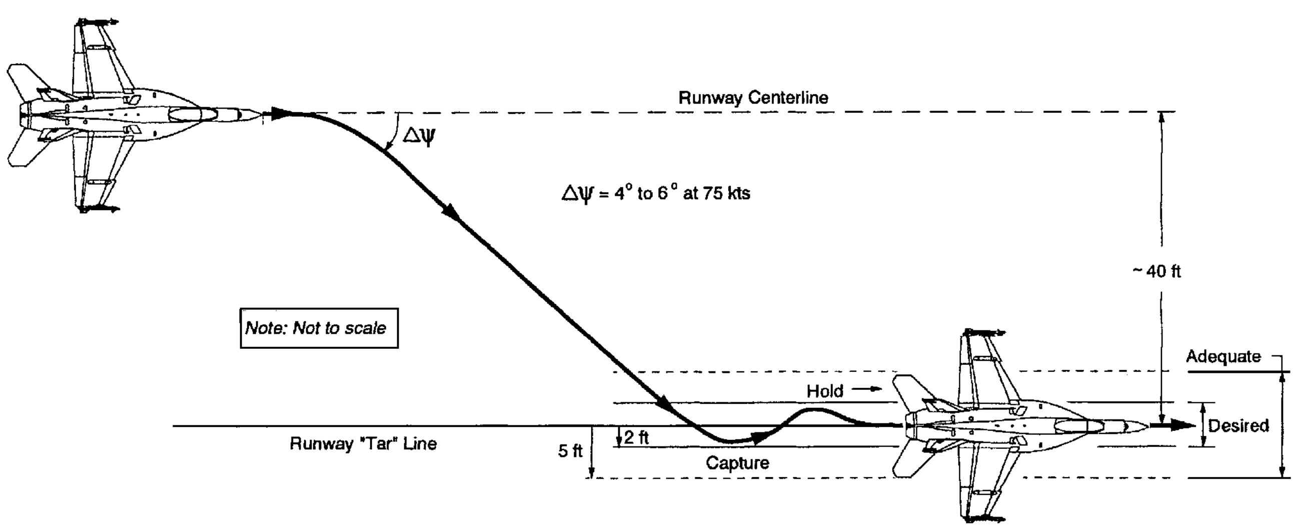


Fig. 3 ROCH.

particular configuration can rarely be adequately assessed in a single event, the pilot is encouraged to continue with additional captures. Runway length constraints may require repeat evaluation runs before comments are given and ratings are assigned. As mentioned in the description, the maneuver should be attempted at a number of speeds. Note that speed should be held constant for a given evaluation. To maintain a common level of aggressiveness, the range of the initial intercept angle shallows as speed increases. This maneuver has been used to evaluate the ground handling of several U.S. Navy aircraft.

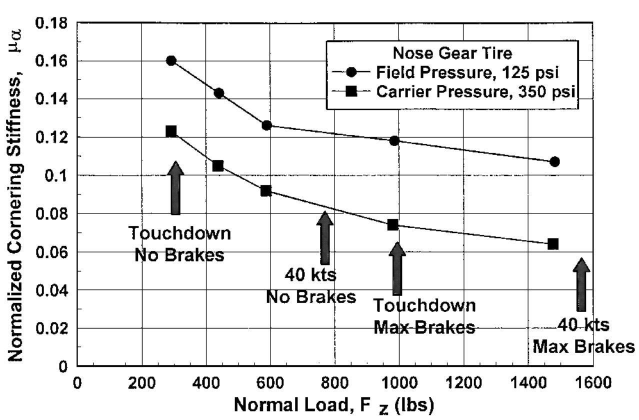
Tire Test Data

Under contract to the The Boeing Company, the tire research division of Veridian Engineering conducted extensive testing of the main and nose gear tires of a U.S. Navy jet trainer. The Veridian tire test facility features a belt driven system, as shown in Fig. 4, that can accommodate a wide range of tires from automobiles to trucks to aircraft. The apparatus can simultaneously control tire slip angle; inclination angle, that is, camber; normal load; longitudinal slip ratio; and speed. For the evaluation, 7 nose and 14 main gear tires were used. Runs were conducted at both field and carrier pressures, that is, 125 and 350 psi, respectively, at a velocity of 60 mph on a 120 Polycut simulated roadway surface that is representative of the frictional properties of a dry runway. The test matrix included cornering (slip angle sweeps) runs for both the nose and main gear tires and braking (longitudinal slip ratio sweeps) and combined cornering and braking runs (longitudinal slip ratio sweeps at various slip angles) for the main gear tires.

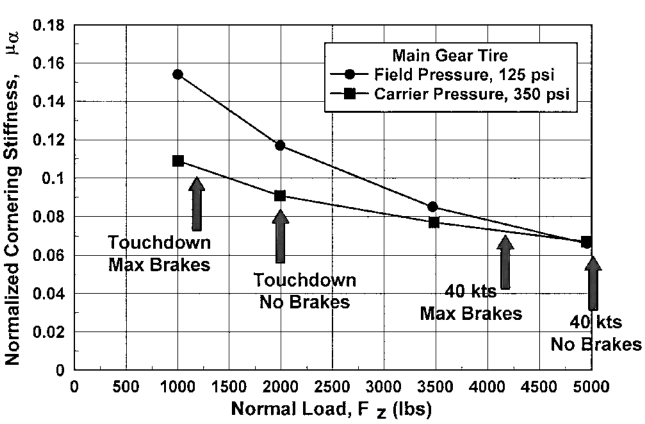
Figure 5 shows the variation of normalized cornering stiffness, $\mu_\alpha = Y_\alpha / F_z$, with normal load for the Veridian nose and main tire data at 125 and 350 psi. Included are pointers to the normalized cornering stiffness values associated with nose and main gear tire normal loads at touchdown (approximately 120 kn) and 40 kn with and without braking. At the lower normal loads, the Veridian data indicate increasing normalized cornering stiffness with decreasing load, the expected result per Ref. 3. Figure 5a (nose tire) also indicates a significant pressure effect. At the lower normal loads, that is, 300, 450, and 600 lb, the 350-psi data have a more than 30% reduction in normalized cornering stiffness and at the higher normal loads, that is, 1000 and 1500 lb, this reduction exceeds 60%. The main tire data, on the other hand, show little or no pressure effect at high normal loads. As normal load decreases, the high-pressure main tire data diverge from the low-pressure data to about a 30% difference at the lowest normal load.

These data reveal that inflating the main gear tires to 125 psi maximizes the cornering stiffness of the rear "axle" whereas inflating the nose tires to 350 psi significantly reduces the cornering stiffness of the front axle. This provides a scenario for improving the understeer gradient and heading attitude bandwidth of the aircraft without making configuration changes other than to tire service pressure. It is the observed reduction in nose tire cornering stiffness at the higher tire pressure that resulted in the recommendation to perform the ground-handling flight tests described herein.

Although the overall character of the normalized side force stiffness is similar for both the nose and main gear tires, Fig. 5 does reveal differences that arise from at least two important sources. First, the main gear tires are larger in size and are designed primarily to absorb



a) Nose gear tire



b) Main gear tire

Fig. 5 Normalized cornering stiffness comparisons.

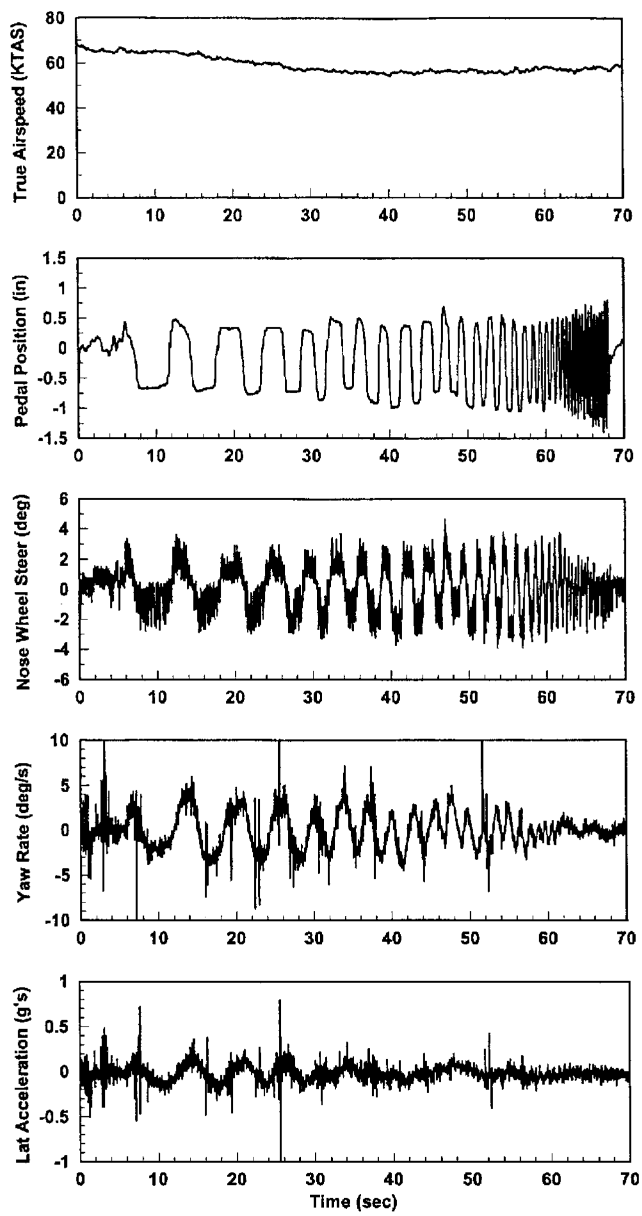


Fig. 6 Example rudder pedal frequency sweep time histories from F1160/R18 at 60 kn.

the high sink rates associated with carrier landings. Second, the main gear tires operate in a much higher normal load range than the nose gear tires. When only normal loads below 2000 lb are considered, for example, the characteristics of the tires are quite similar.

Flight-Test Results

Program Description

The Naval Air Warfare Center Aircraft Division at Patuxent River Naval Air Station conducted a two-phase flight-test program to evaluate the ground handling of a U.S. Navy trainer with nose tires inflated to carrier service pressure against the baseline aircraft configuration, that is, all tires set to field service pressure. Phase 1 took place in February 2001 and consisted of a series of 1) rudder pedal frequency sweeps from which the heading attitude bandwidth of the high-pressure nose tire configuration was determined as a function of speed and 2) pilot evaluations of the ROCH maneuver. Based on the success of these evaluations, a second phase was conducted in April 2001 to provide additional pilot opinion data, again using the ROCH maneuver. Earlier flight-test evaluations of the baseline configuration from June 2000 provided both heading attitude bandwidth and ROCH pilot opinion data that are included in the results presented herein.

Bandwidth Comparisons

Rudder pedal frequency sweep data were collected at 40, 60, 80, and 100 kn. Several runs were conducted at each speed. The first run attempted to capture the low-frequency range of interest, that is, 0.1–0.5 Hz, whereas the second attempted to capture the high-frequency range of interest, that is, 0.5–3.0 Hz. Figure 6 shows rudder pedal sweep time histories for an example 60-kn, high-frequency input run. The signals included in the strip chart are true airspeed, rudder pedal position, nose wheel steering angle, yaw rate, and lateral acceleration. These parameters were used to identify the directional response of the aircraft alone (r/δ_{NWS}), the nose wheel actuator (δ_{NWS}/δ_p), and the aircraft plus actuator (r/δ_p). The analysis presented herein focuses on the aircraft plus actuator (r/δ_p) response that is used to determine the heading attitude bandwidth parameters.

A specialized fast Fourier transform (FFT) software package, FREDA, developed by STI, was used to compute the yaw rate to rudder pedal frequency responses from both the frequency sweep

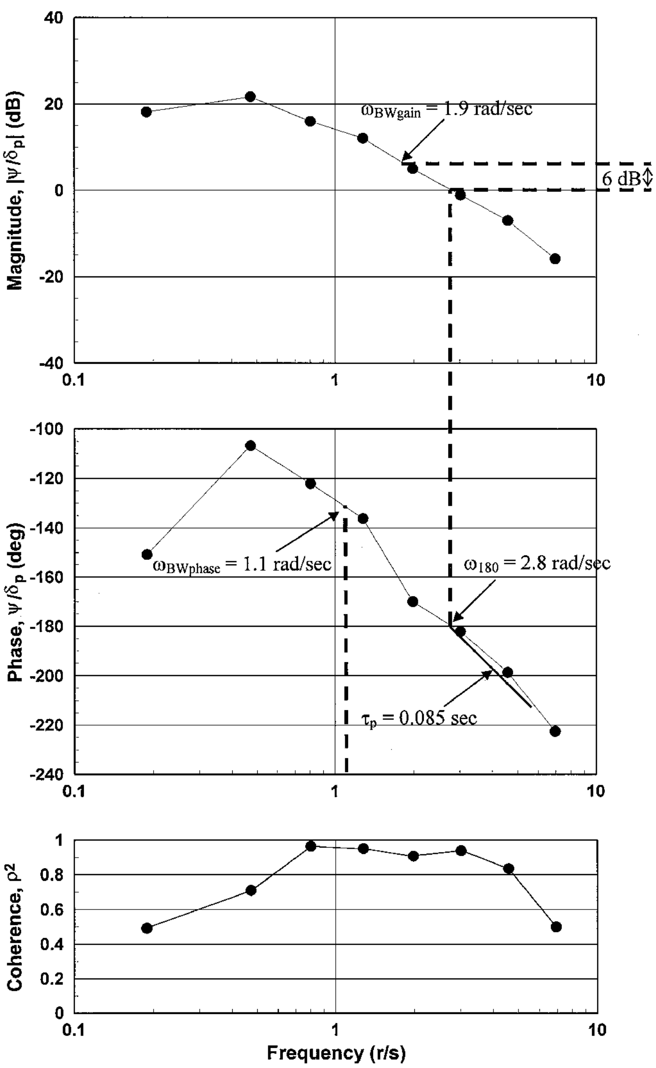


Fig. 7 Heading attitude to rudder pedal position (ψ/δ_p) frequency response from F1160/R18 at 60 kn.

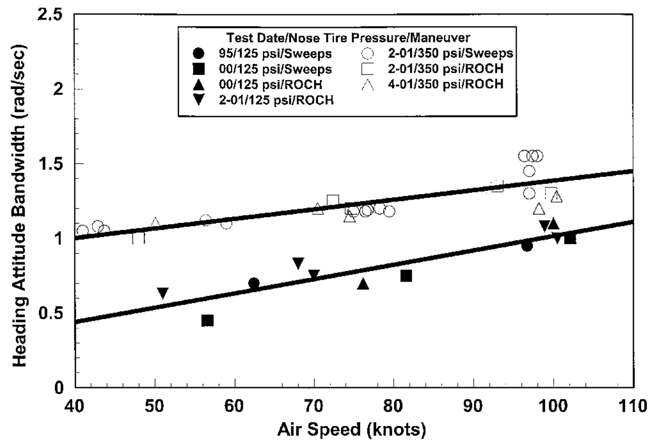
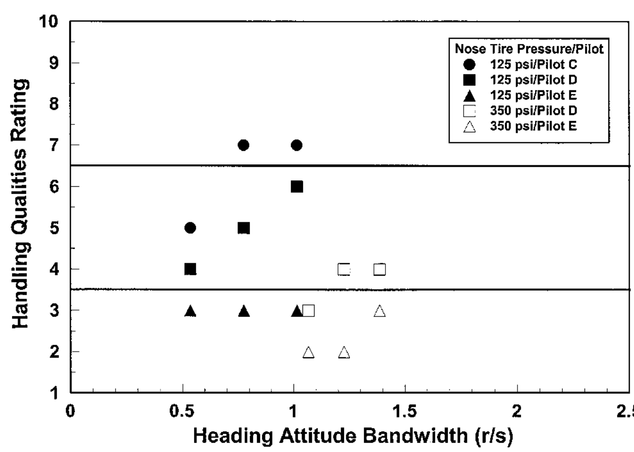
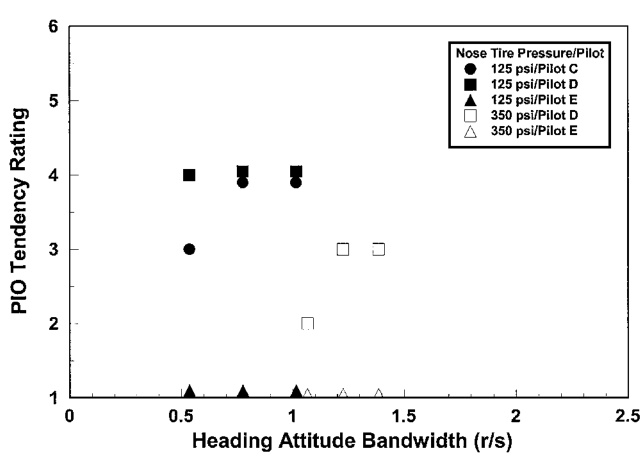


Fig. 8 Improvement in heading attitude bandwidth with high-pressure nose tires.



a) Handling-qualities ratings



b) PIO tendency ratings

Fig. 9 ROCH pilot ratings vs heading attitude bandwidth.

and ROCH time histories. In addition to analyzing each run individually, the signals from selected runs at a given speed were combined to produce one "long run" that maximized the data used in the FFT. In general, the yaw rate signal provided higher quality data than the heading angle signal. The heading attitude response for each run was, therefore, approximated from the computed yaw rate to rudder pedal response. When the definitions described earlier were used, the bandwidth parameters were calculated for each run. The identification of these parameters from the 60-kn sweep of Fig. 6 is shown in Fig. 7, which includes the Bode magnitude and phase responses and the coherence. Note that only high-coherence data, that is, $\rho^2 > 0.65$, were used to compute the bandwidth parameters.

All available heading attitude bandwidth data were used to create the bandwidth vs air speed plot shown in Fig. 8. This includes the rudder pedal frequency sweeps from phase 1 with the high-pressure nose tires and all of the ROCH runs from both phases 1 and 2. In addition, baseline configuration frequency sweep and ROCH bandwidth data that were obtained from earlier flight-test programs have also been included. The trend lines represent linear regression fits to the available data. Note that as hypothesized from the tire test data a significant improvement in heading attitude bandwidth (and understeer gradient) for the high-pressure nose tire configuration is observed across the air speed range.

Pilot Rating Comparisons

The improvement in heading attitude bandwidth with the high-pressure nose tires is also reflected in the pilot ratings assigned for the ROCH task as shown in Fig. 9. (Note that the plots also include ROCH ratings that were collected in the June 2000 ground-handling flight tests with the baseline aircraft configuration.) For pilot D there is a one–two handling-qualities rating point improvement and a one PIO tendency rating point improvement with the increased bandwidths associated with the high-pressure nose tires. Although pilot D clearly preferred the high-pressure nose tire configuration, he could still not attain level 1 handling qualities across the speed range, that is, for 75 and 100 kn desired performance was attained, but moderate pilot compensation was required. The ratings of pilot E, on the other hand, did not reflect significant differences between the two nose tire configurations. Furthermore, the level 1 ratings for all evaluations did not indicate the significant handling qualities deficiencies reflected in the ratings of the other two pilots. In his comments, however, pilot E did express a clear preference for the high-pressure nose tire configuration. "The decreased workload and pedal inputs with the nose wheel tires inflated to 350 psi would benefit ground handling."

The interpilot differences are seen most in the PIO tendency ratings. Both pilots C and D observed strong PIO tendencies especially

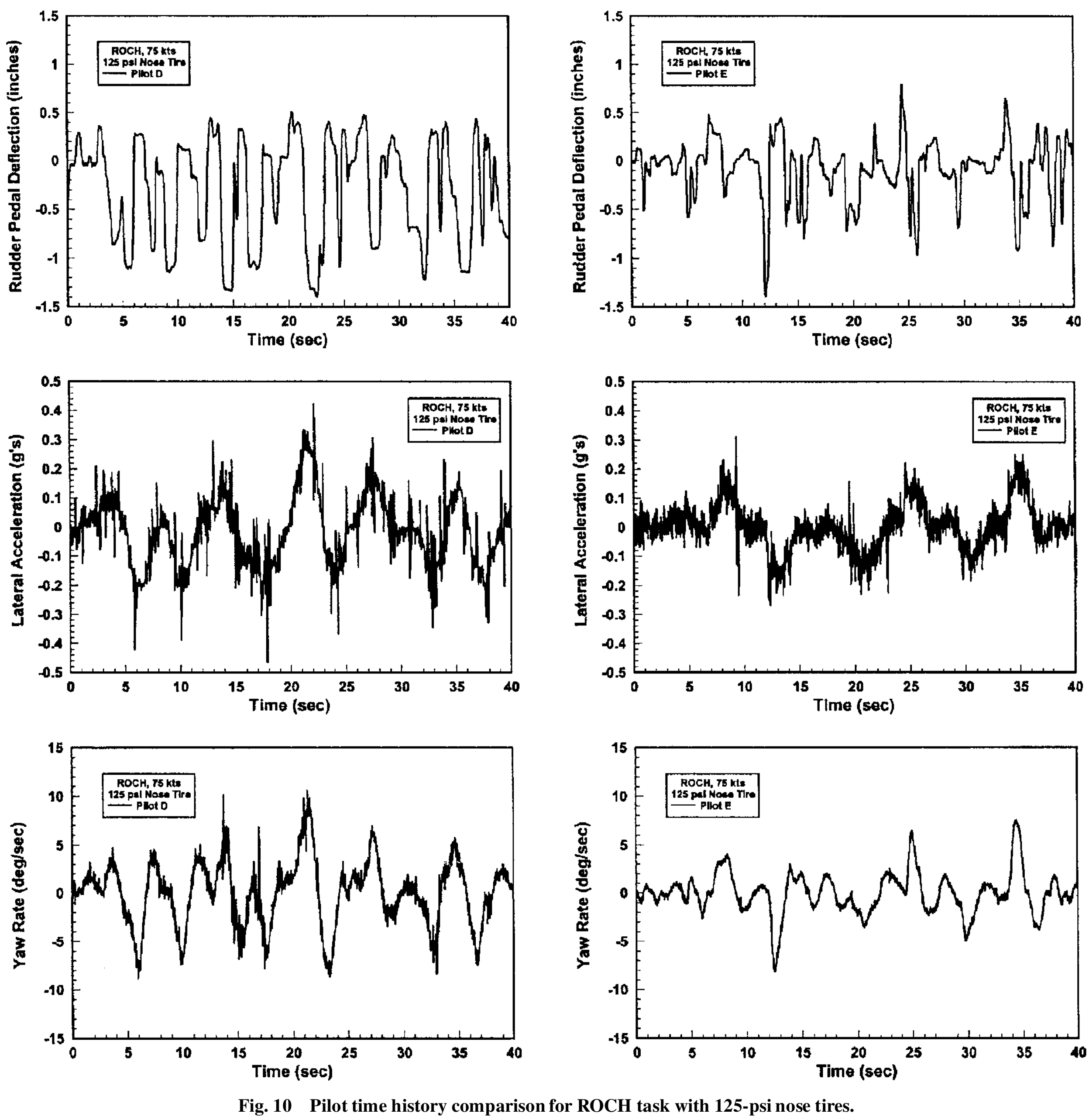


Fig. 10 Pilot time history comparison for ROCH task with 125-psi nose tires.

with the baseline configuration. In the words of the PIO tendency rating scale[9,10] the rating of 4 indicates that "oscillations tend to develop when pilot initiates abrupt maneuvers or attempts tight control. Pilot must reduce gain or abandon task to recover." Pilot E, however, did not observe any PIO tendencies in the ROCH task as indicated by the PIO ratings of 1, no tendency for pilot to induce undesirable motions, given to all configurations. It is postulated here that these differences arise from pilot technique. That is, pilot E used a more open-loop technique based on a highly skilled ability to time and size commanded rudder pedal inputs to meet the task performance requirements and, thus, avoided the need for significant closed-loop control actions. Therefore, he could appropriately be given the call sign "Golden Foot." This hypothesis is examined further in the following section.

Time History Comparisons

To examine differences in piloting technique between pilots D and E, time history comparison plots for ROCH evaluations at 75 kn with the baseline configuration are provided in Fig. 10. Included in Fig. 10 are the rudder pedal inputs of the pilots and the resulting lateral acceleration and yaw rate output responses. In his attempts to perform the task, Pilot D used continuous, large-amplitude rudder pedal pulses of approximately 1-s duration. The inputs are also strongly biased to the left pedal. Pilot E, on the other hand, initiated his capture with a quick, relatively high-amplitude doublet followed by several smaller amplitude inputs to hold the new position. He also preferred to "wait and see" the impact of a given input, rather than employ continuous corrections. The more aggressive approach of pilot D naturally resulted in higher lateral accelerations and yaw rates. Similar comparisons were observed with the example time responses for the high-pressure nose tire configurations (not shown). These results indicate that pilot D clearly employed a more aggressive, continuous closed-loop control technique when compared to pilot E. Such a technique would be more likely to expose the handling-qualities deficiencies that were reflected in the associated ratings and in particular the observed PIO tendencies of the baseline configuration.

Conclusions

Comprehensive tire tests were conducted as part of an ongoing investigation of the ground handling of a U.S. Navy trainer. It was observed that an improvement in aircraft understeer gradient and heading attitude bandwidth could be achieved with the nose tires inflated to the higher carrier service pressure. A two-phase flight-test program was conducted to provide heading attitude bandwidth data as a function of air speed and pilot evaluations of ground handling while performing a ROCH task. Frequency-domain analysis of the flight-test data revealed a significant improvement in heading attitude bandwidth for the high-pressure nose tire configuration across the tested air speed range. One evaluation pilot noted a one–two handling qualities rating point improvement and a one PIO tendency rating point improvement with the increased bandwidths associated with the high-pressure nose tires. Although not reflected in his ratings, the second evaluation pilot did express a clear preference for the high-pressure nose tire configuration. A review of the time history data generated by the two pilots indicated that the pilot with the more diverse ratings between the two aircraft configurations clearly employed a more aggressive, continuous closed-loop control technique. Such a technique was more likely to expose the handling-qualities deficiencies that were reflected in the associated ratings and in particular the observed PIO tendencies of the baseline configuration.

One concern associated with the high-pressure nose tire configuration is the potential for increased tread wear; however, discussions with the tire manufacturer have alleviated this concern. Because in the carrier environment the aircraft routinely operates with tires inflated to the higher pressure, the likelihood of transmitting excessive loads to the aircraft structure is not increased. No significant disadvantage of the high-pressure nose tire configuration has, thus, been identified. Before use of this configuration within the fleet, performance in crosswind and wet runway conditions will be assessed.

Acknowledgments

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