JOURNAL OF GUIDANCE, CONTROL, AND DYNAMICS
Vol. 25, No. 3, May–June 2002

Identification of the Dominant Ground Handling Characteristics of a Navy Jet Trainer

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An assessment is described of the ground handling problems associated with a Navy jet trainer including the lower-order equivalent systems modeling approach that was used to determine the dominant ground handling characteristics, that is, oversteer/understeer. It was found that just after touchdown the aircraft may 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. 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.

Nomenclature

a	=	longitudinal distance from nose gear tire to c.g.
B	=	first-order denominator coefficient of yaw rate to steering command transfer function
b	=	longitudinal distance from main gear tire to c.g.
C	=	zero-order denominator coefficient of yaw rate to steering command transfer function
C_{n_β}	=	aerodynamic yaw moment to sideslip angle nondimensional stability derivative
F_x	=	tire longitudinal force
F_y	=	tire side force
F_z	=	tire normal load
g	=	gravitational constant
K	=	stability factor
k	=	pilot–vehicle system gain
l	=	vehicle wheel base, $a + b$
m	=	vehicle mass
N_r	=	yaw moment to yaw rate dimensional stability derivative
N_v	=	yaw moment to lateral velocity dimensional stability derivative
N_{δ_w}	=	yaw moment to steering command dimensional control derivative
p	=	tire inflation pressure
R	=	effective tire radius
r	=	yaw rate
S	=	tire longitudinal slip ratio
s	=	Laplace operator
UG	=	understeer gradient
U_c	=	vehicle critical speed
U_0	=	vehicle ground speed
u	=	wheel hub velocity
v	=	lateral velocity
Y_r	=	side force to yaw rate dimensional stability derivative
Y_v	=	side force to lateral velocity dimensional stability derivative
$Y_{\alpha 1}$, $Y_{\alpha 2}$	=	front and rear dimensional tire cornering stiffnesses
Y_{δ_w}	=	side force to steering command dimensional control derivative
α	=	tire slip angle
δ_w	=	steering command
μ_α	=	normalized tire cornering stiffness
Φ_M	=	phase margin
ψ	=	yaw attitude angle
ω	=	frequency or wheel angular velocity
ω_c	=	pilot–vehicle system crossover frequency
$1/T_{\text{lag}}$	=	pilot describing function lag
$1/T_{\text{lead}}$	=	pilot describing function lead
$1/T_r$	=	yaw rate numerator inverse time constant
$1/T_1$	=	low-frequency real root of the yaw rate to steering command transfer function for an oversteer vehicle
$1/T_2$	=	high-frequency real root of the yaw rate to steering command transfer function for an oversteer vehicle

Introduction

SYSTEMS Technology, Inc. (STI) was contracted to perform an assessment of the ground handling of a Navy jet trainer. STI worked closely with The Boeing Company and the U.S. Navy on a number of tasks that included linear modeling, ground handling metric and maneuver development, and the evaluation of proposed fixes to the ground handling deficiencies as exemplified by the example 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. The source of these deficiencies is identified and discussed later in the paper.

This paper presents results and interpretations from the analytical effort that was undertaken to uncover the dominant directional characteristics of the aircraft. Three mathematical models of the aircraft in rollout were used in a highly coordinated manner in this study: 1) the Boeing modular six-degree-of-freedom (MODSDF) simulation, 2) the two-degree-of-freedom bicycle model, and 3) the STI three-degree-of-freedom lower-order equivalent system (LOES) ground vehicle model. The Boeing MODSDF simulation has long been used for ground handling analysis and is closely related to and coordinated with the model used in the Boeing simulator. The two-degree-of-freedom yaw–sideslip bicycle model is the

Received 20 February 2001; revision received 13 September 2001; accepted for publication 20 September 2001.

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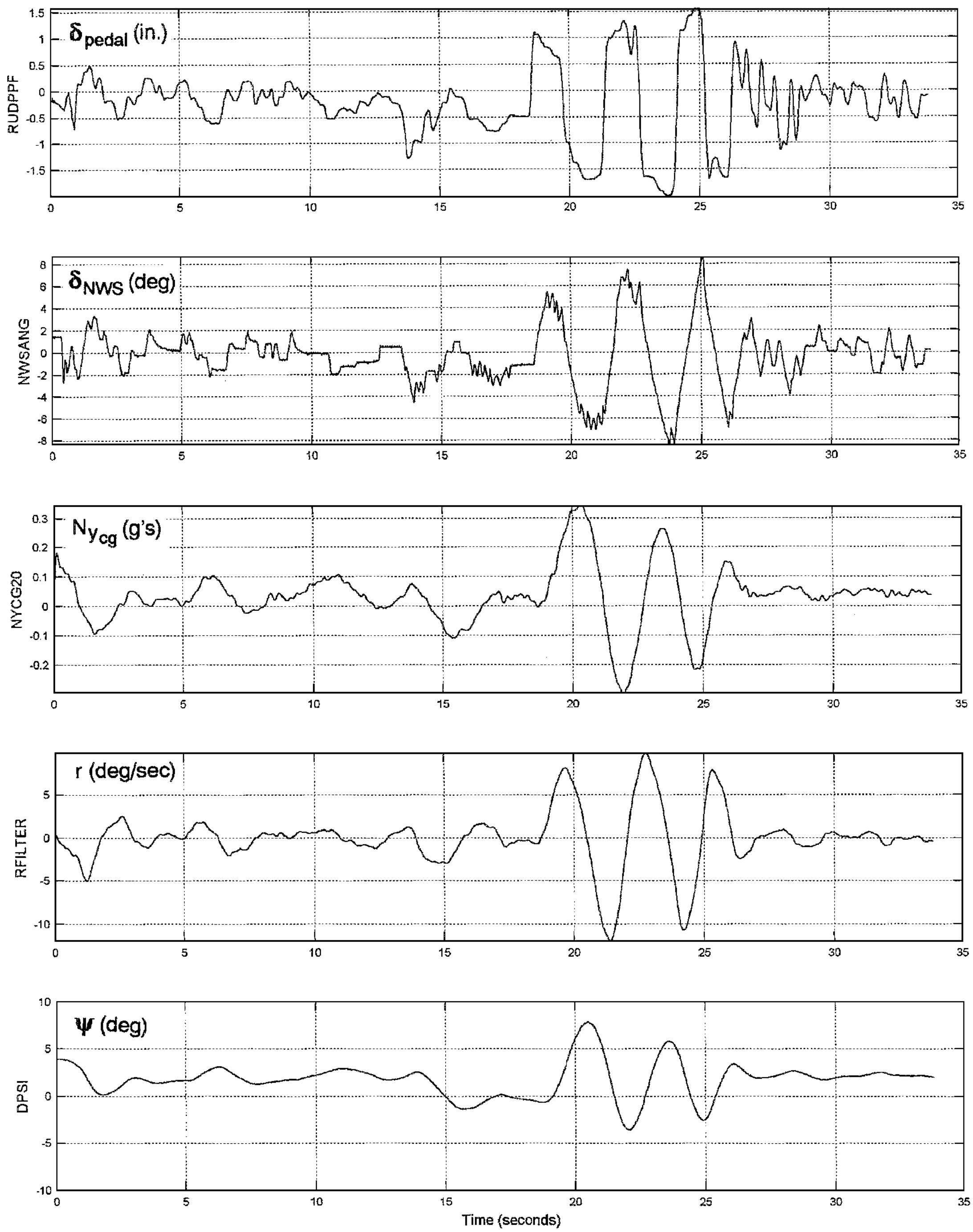

Fig. 1 Example flight-test ground handling PIO: high-speed landing rollout centerline crossing task.

simplest commonly used model for automobiles. With some important conceptual refinements, this model has been very important in understanding aircraft dynamics. The STI LOES model has been used primarily in the system identification process. It is similar to the bicycle model but adds some details, such as the roll degree of freedom that improves parameter estimation.

LOES Approach

Background

The best understanding of the critical oversteer/understeer characteristic is obtained not from the most complex simulation model, but rather from the simplest analytical model. Thus, in this project, particular emphasis was placed on the use of LOES models as a complement to high-level, detailed simulations. LOES models provide unique physical insight and help separate the key dynamics from second-order effects. The STI philosophy of reduced-order modeling is to seek the simplest model that captures the dominant dynamics. This is distinct from the usual emphasis on making nonlinear simulation as detailed as possible to avoid missing something. LOES models and detailed nonlinear simulation, that is, MODSDF, were used together for mutual validation based on available flight-test data.

The simplest, and in many ways the most important, LOES model is the bicycle model.[1,2] This two-degree of freedom (yaw–sideslip) model assumes the axle track widths are zero so that the tires on each axle are lumped together. Despite the simplicity of this model, it has proven widely useful in the analysis of automobile dynamics. The bicycle model provides an indication of how adequately the yaw attitude dynamics of the vehicle can be defined without considering the second-order effects of lateral load transfer and roll dynamics. In general, the yaw–sideslip dynamics are the dominant characteristics in ground vehicle handling. Based on its significant utility for automobile handling assessment, this simple model was expected to be quite useful for aircraft as well. In any case, it was felt that the basic yaw–sideslip dynamics should be thoroughly understood before considering other issues and degrees of freedom.

The bicycle model allows the simplest formulation of the yaw response to steered (front/nose) wheel transfer function, which is central to understanding the ground handling qualities. This in turn provides the basis for defining the oversteer/understeer gradient (and the closely related stability factor) in terms of the key physical parameters. The important insight from this approximate analysis is that the oversteer/understeer gradient is essentially a function of the difference between the front and rear tire cornering stiffnesses. To a first approximation, increasing the front (nose wheel) tire cornering stiffness with respect to the rear (main gear) makes the vehicle less understeer or more oversteer. Cornering stiffness, the derivative of tire lateral force with respect to slip angle, thus, becomes the primary design variable for achieving a desired understeer characteristic, that is, unless the dynamics are modified with an active control system.[1] This in turn makes the determination of tire cornering stiffness using tire test data an item of great importance.

Cornering stiffness as used here is a function of four primary tire variables: 1) lateral slip angle, 2) longitudinal slip (which is significantly influenced by braking), 3) normal load, and 4) inflation pressure. Tire camber is also an influence, but more so for bicycles and motorcycles than for aircraft. Further, inflation pressure is generally approximately constant during a given operational scenario. The effect of lateral slip angle is exploited to steer the vehicle. The influence of longitudinal slip (braking) and tire normal load tend to change the oversteer/understeer gradient toward oversteer from the nominal (design) value in braking. Because only the main gear wheels of the aircraft have brakes, longitudinal slip always tends to reduce directional stability. The influence of normal load is more complex and can increase or decrease directional stability. This complexity arises from 1) the nonlinearity of the basic tire characteristic, 2) the influence of aerodynamics (especially for aircraft) on the normal load, and 3) load transfer in braking and maneuvering.

Not surprisingly, the various aerodynamic effects provide the most significant differences in ground handling dynamics between automobiles and aircraft. To exploit the large body of theoretical analysis and empirical data for automobile handling, a clear understanding of the fundamental differences, as well as the similarities, between the dynamics of automobiles and those of aircraft as well as the design considerations that create the differences is required. As noted earlier, aerodynamics is a relevant issue in this connection and influences the vehicle dynamics in two ways: 1) indirectly through its influence on tire normal force and 2) directly through the influence on the aerodynamic directional stability largely determined by the vertical stabilizer. The indirect effect is influenced not only by the lift, but also by the drag and pitching moment and their variation with speed, that is, dynamic pressure. The direct effects can be approximated as aerodynamic stability and control derivatives with respect to yaw and sideslip. Both the direct and indirect aerodynamic influences decrease with dynamic pressure as aircraft ground speed diminishes. However, the speed variation of the indirect effect is more complex.

The effects of aerodynamics on automobiles and aircraft differ largely from the simple fact that aircraft are specifically designed to generate significant aerodynamic forces. Further, aircraft touchdown speeds are high compared to typical automobile speeds, and these speeds change rapidly over a large range in the ground roll. In many applications of the bicycle model to automobiles, it is reasonable and routine to neglect aerodynamic effects. Therefore, tire normal loads and, thus, the oversteer/understeer gradient are invariant with speed. As will be seen, the assumption of constant stability factor is not reasonable for aircraft in ground roll. Thus, strictly speaking, a linearized model of the aircraft such as the bicycle model should be treated as a system with time-varying coefficients. Such analysis is, however, complex and probably best accomplished with nonlinear simulation, in this case MODSDF. Again, the purpose of the LOES bicycle model is to achieve insight through simplifying approximations. Therefore, a useful approximation is to decompose the problem into two parts. First, compute the variation of stability factor with ground speed, which is a problem of static equilibrium, not dynamics. Then, at any given speed, the dynamics can be assessed to a first approximation by applying the stability factor to the bicycle model.

Two-Degree-of-Freedom Model

The two-degree of freedom bicycle model provides an indication of how adequately the yaw attitude dynamics of the vehicle can be defined without considering the second-order effects of lateral load transfer and roll dynamics. In general, the yaw–sideslip dynamics are the dominant effects in ground vehicle handling. Thus, the basic yaw–sideslip dynamics should be thoroughly understood before considering other degrees of freedom.

The bicycle model state space equations of motion in the s-domain as reviewed in Ref. 1 are

$$\begin{bmatrix} s - Y_v & U_0 - Y_r \\ -N_v & s - N_r \end{bmatrix} \begin{bmatrix} v \\ r \end{bmatrix} = \begin{bmatrix} Y_{\delta_w} \\ N_{\delta_w} \end{bmatrix} \delta_w \tag{1}$$

The bicycle model stability and control derivatives are defined as follows:

$$Y_v = -(2/mU_0)\left(Y_{\alpha_1} + Y_{\alpha_2}\right), \qquad N_v = \left(2\big/mk_z^2 U_0\right)\left(bY_{\alpha_2} - aY_{\alpha_1}\right)$$

$$Y_r = (2/mU_0)\left(bY_{\alpha_2} - aY_{\alpha_1}\right)$$

$$N_r = -\left(2\big/mk_z^2 U_0\right)\left(a^2 Y_{\alpha_1} + b^2 Y_{\alpha_2}\right)$$

$$Y_{\delta_w} = (2/m)Y_{\alpha_1}, \qquad N_{\delta_w} = \left(2a\big/mk_z^2\right)Y_{\alpha_1}$$

Examination of the bicycle model indicates that these equations of motion contain seven independent parameters: vehicle speed, vehicle total mass, radius of gyration about the body z axis, front and rear longitudinal distances between the tire axles and the c.g., and front and rear (dimensional) tire cornering stiffnesses. Of these seven parameters, all are independent of speed except, of course, U_0. This would not be strictly true if the steady aerodynamic forces were included because the tire normal loads would change as the lift, drag, and pitching moment decrease during rollout. The six remaining parameters are somewhat dependent on operational conditions to the extent that weight varies slightly among landings with the amount of fuel remaining. This affects mass and radius of gyration directly and tire-cornering stiffness indirectly through the influence on tire normal force. Small changes in a and b would occur due to variations in c.g. location, but the wheelbase, $l = a + b$, is a geometric constant.

Stability Factor and Understeer Gradient

The static and dynamic stability of automobiles is routinely expressed in terms of either stability factor K (seconds squared per squared foot) or understeer gradient UG (degrees per gravity constant), which are readily developed from the bicycle model. These two parameters are defined as follows and are closely related and routinely used interchangeably:

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

These parameters arise from the steady-state yaw rate to steering command gain $G^r_{\delta_w}(0)$ (per second) as follows:

$$G^r_{\delta_w}(0) = U_0\big/(a+b)\left(1 + KU_0^2\right) \tag{3}$$

As shown in Fig. 2, when $K = 0$, the vehicle is said to have neutral steer, and the yaw rate gain increases in proportion to speed. In contrast, when $K > 0$, the vehicle has 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 has oversteer. Above the critical speed U_c, the vehicle becomes directionally unstable:

$$U_c = 1\big/\sqrt{-K} \tag{4}$$

The oversteer characteristic is generally considered an inappropriate handling characteristic for ordinary drivers (or student pilots), although racing cars often are setup to be oversteer for increased agility.

For automobile handling qualities assessments, K and UG can sometimes be usefully considered invariant with speed. Aircraft, on

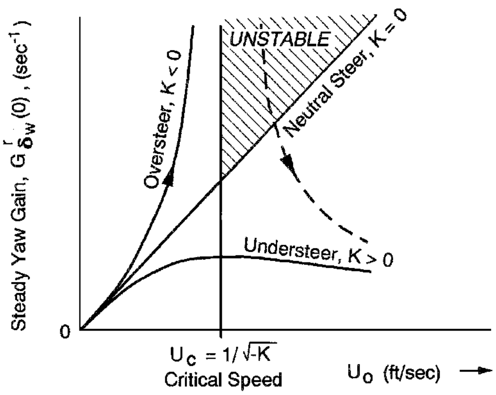

Fig. 2 Oversteer/understeer as a function of speed.

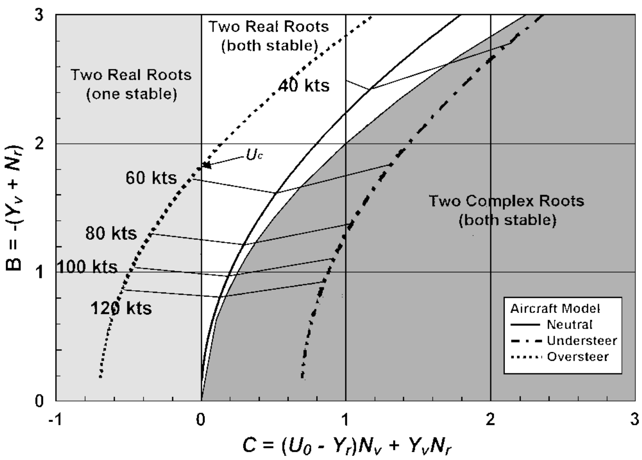

Fig. 3 Categorization of aircraft characteristic roots in the $B-C$ parameter plane.

the other hand, produce significant variation in stability factor with speed. As already noted, the solution can be usefully approximated by decomposing the problem into two parts: 1) a static equilibrium problem, in which stability factor is calculated as a function of speed, and 2) a constant coefficient linear dynamics problem, for example, the simple bicycle model.

Yaw Rate to Steering Command Transfer Function

The most fundamental dynamic characteristic relevant to ground handling is the yaw rate to steering command transfer function, which is central to understanding manual yaw attitude control. This transfer function is

$$\frac{r}{\delta_w}(s) = G^r_{\delta_w}(s) = \frac{N_{\delta_w}\left(s - Y_v + N_v Y_{\delta_w} \big/ N_{\delta_w}\right)}{\left[s^2 - (Y_v + N_r)s + (U_0 - Y_r)N_v + Y_v N_r\right]}$$

$$= \frac{N_{\delta_w}(s + 1/T_r)}{[s^2 + Bs + C]} \tag{5}$$

The stability of the vehicle is revealed in the eigenvalues of the characteristic polynomial that vary with the coefficients B and C that in turn are set by tire and aerodynamic characteristics. The $B-C$ parameter plane can be divided into three regions according to the character of the eigenvalues, as shown in Fig. 3. Figure 3 features three curves that display the variation of B and C with speed for oversteering, neutral, and understeering aircraft models. Note that the understeering and oversteering models in this example differ only by the sign of the stability factor K. As indicated in Fig. 3, understeering vehicles tend to have two stable complex conjugate poles such that the dynamics are stable, but possibly lightly damped at high speeds. Neutral steer vehicles tend to have two stable real roots, $1/T_1$ and $1/T_2$. Oversteering vehicles have two real roots as well, one of which, $1/T_1$, becomes unstable above the critical speed U_c.

Variation of Yaw Rate to Steering Command Response with Speed for a Fixed Stability Factor

The yaw rate to steering command transfer function can be most usefully interpreted from a frequency response or Bode plot. Examples are shown at three speeds in Fig. 4: below, at, and above the critical speed for an aircraft with a constant oversteer stability factor ($K = -0.000107$ s^2/ft^2 approximates to the Navy trainer at about 55 kn). The low-speed characteristic (35.5 kn) shows a yaw rate command characteristic in which the frequency response is flat up to the dominant pole $1/T_1$. The bandwidth of the yaw rate command characteristic is effectively set by the width of this flat shelf. Bandwidth is a primary handling qualities parameter,[3] and it determines how rapidly the pilot will see an essentially constant yaw rate response to a step pedal command. That is, the rise time of the yaw rate command response is inversely proportional to the bandwidth.

Even though the stability factor is the same in this example, the yaw rate response is distinctly different near the critical speed U_c. Here the dominant pole $1/T_1$ has moved to very low frequency, and consequently, the yaw rate command bandwidth has practically vanished. This is a very adverse situation for the manual control of yaw attitude because a step pedal command produces yaw acceleration rather than a constant yaw rate. This accelerationlike characteristic can lead to pilot–vehicle instability, that is, PIOs, when the pilot attempts closed-loop manual control of yaw attitude either in maneuvers or in the presence of gusts.

Well above the critical speed, the bandwidth increases, but the $1/T_1$ pole is now unstable as evidenced by the phase curve approaching -180 deg at low frequency. Experienced pilots (and race car drivers) can exploit the controllability afforded by adequate yaw rate bandwidth to stabilize the vehicle manually, but this may be difficult for a student pilot (or an average driver).

The variation of stability factor with speed is significant for aircraft. This complicates the determination of stability factor, but the interpretation for a given K remains the same. That is, the location of the $1/T_1$ pole, through its direct influence on stability and the yaw rate command bandwidth, is the critical consideration in the dynamics. Furthermore, the dynamics follow from the simple bicycle model once the stability factor has been determined from static equilibrium and knowledge of the tire normal force characteristics.

Tire Force Model

Data from tire tests conducted at the NASA Langley Research Center (LaRC) Aircraft Landing Dynamics Facility and the Veridian Tire Research Facility were used to identify the important parameters that characterize tire performance. The tire side and longitudinal forces are functions of four variables: slip angle α, longitudinal slip ratio S, normal load F_z, and inflation pressure p.

The derivative of tire side force with respect to slip angle defines the very important tire cornering stiffness Y_α, as shown in Fig. 5. 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. 5. 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 (Fig. 5). As exemplified by the main gear tire data, longitudinal slip reduces the cornering stiffness in braking, which thus reduces the stability factor (oversteer increment).

Aerodynamic Effects

As earlier stated, one of the most significant distinctions between the ground handling dynamics of aircraft and automobiles is that the influence of vehicle aerodynamics is, as might be expected, much more significant for aircraft. Aerodynamic influences arise from two distinct effects. The direct aerodynamic effect of the lateral–directional forces includes the aerodynamic stability derivative C_{n_β} that is dominated by the stabilizing effect of the vertical stabilizer. The second indirect aerodynamic effect arises from the influence of the longitudinal aerodynamic forces and moments (lift, drag, and pitching moment) on the tire normal loads and, thus, on the cornering stiffnesses.

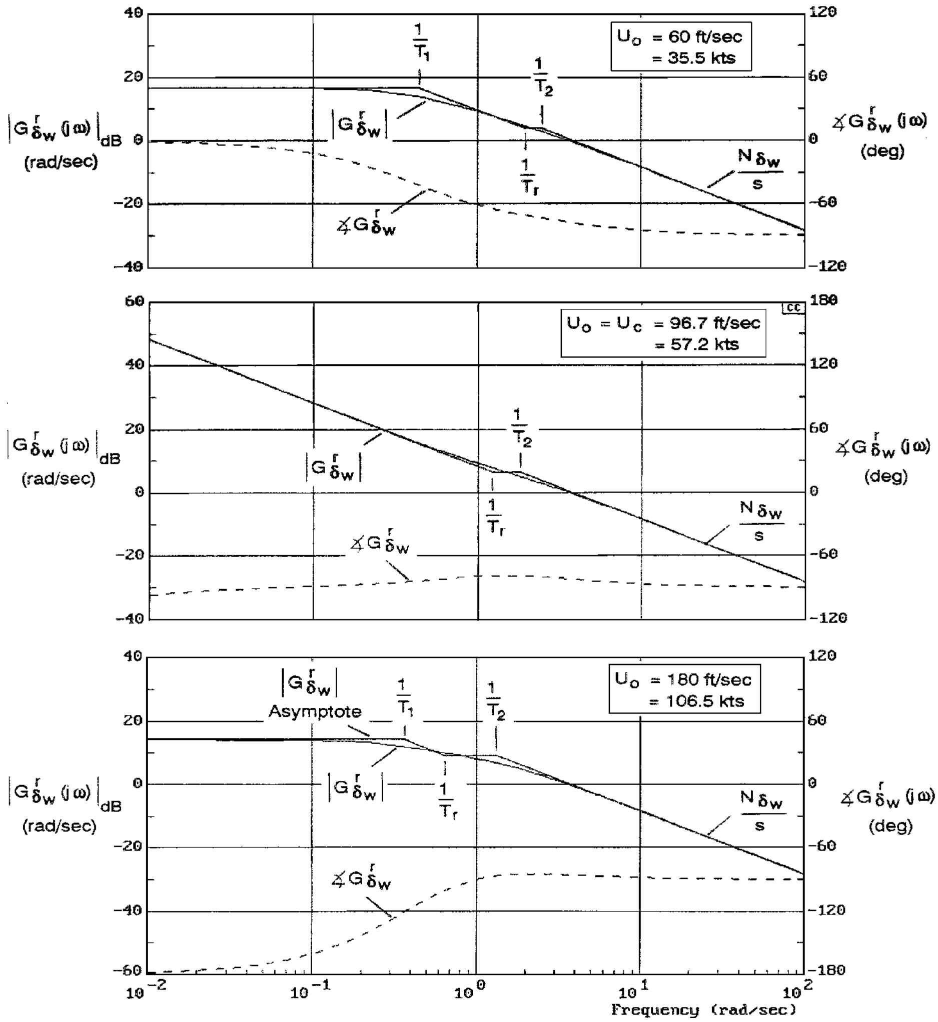

Fig. 4 Yaw rate frequency response to steering command at three speeds ($K = -0.000107$ s^2/ft^2).

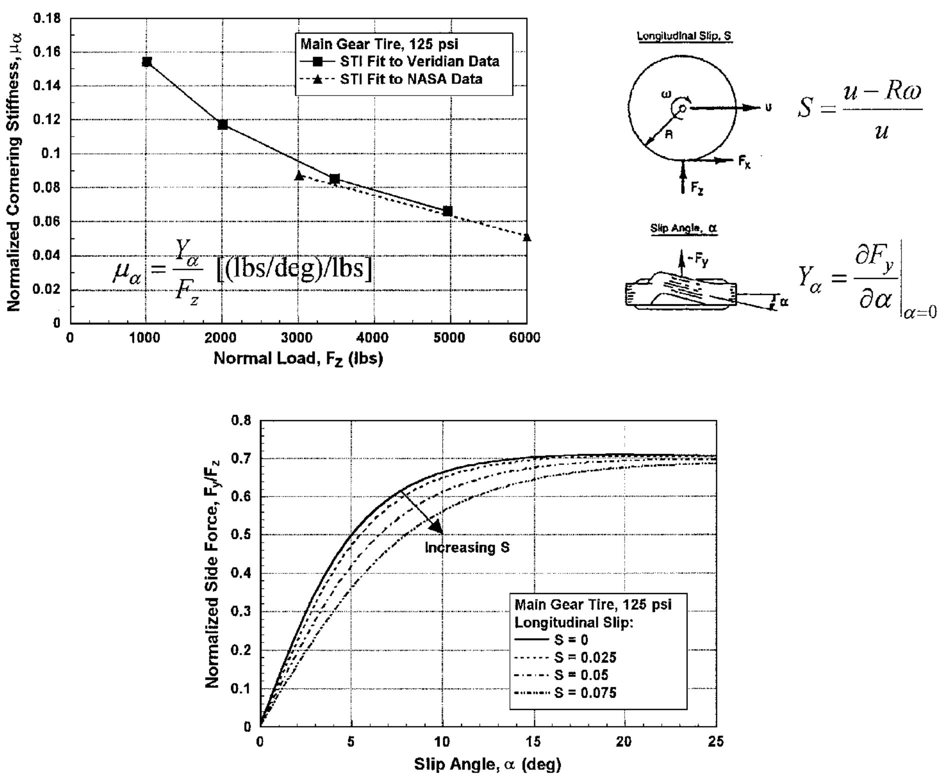

Fig. 5 Main gear tire characteristics.

Variation of Yaw Attitude Dynamics with Speed

Once the aircraft model was refined and validated against test data, it was possible to estimate the variation of understeer gradient (or equivalently stability factor) with speed during rollout. This is shown in Fig. 6 with the direct (lateral–directional) and indirect (longitudinal) aerodynamic influences distinguished. One may see that the aircraft is understeer immediately after touchdown but that the *UG* decreases with speed becoming oversteer below about 80 kn.

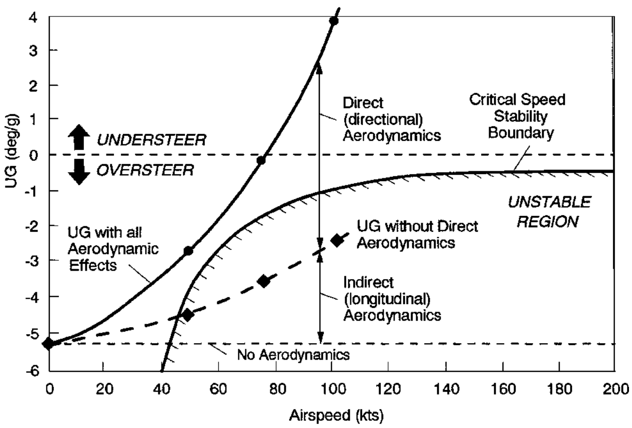

Fig. 6 Understeer gradient as a function of speed.

UG reaches a minimum value of −5.3 deg/g as the speed goes to zero. A very important insight about the yaw attitude control characteristic is seen by comparing the complete *UG* curve to the critical speed stability boundary (hatched curve). It may be seen that, in the important speed range from about 80 kn down to about 40 kn, the aircraft rapidly approaches the stability boundary. Thus, the yaw rate command response has the adverse characteristics of the middle response of Fig. 4. This implies very adverse handling qualities, not because of instability per se, but because the dominant $1/T_1$ pole remains at low frequency, keeping the yaw rate command bandwidth low. In other words, the problem is low controllability rather than instability. Below about 40 kn the aircraft moves beyond the stability boundary, and the handling problems dissipate as the steering dynamics dissolve into simple kinematics.

The role of aerodynamics, both the direct and indirect effects, is revealed to be helpful in that positive (understeer) increments in *UG* are produced that increase with speed. At around 80 kn, the direct and indirect effects are comparable, but the direct effect dominates at higher speeds. This suggests that modulating the indirect effect in the critical ground roll speed regime, through tuning of the pitch trim if feasible, might be helpful in improving yaw attitude control.

Manual Control of Yaw Attitude

Given the yaw rate response to nose wheel steering characteristic of the Navy trainer, the pilot's yaw attitude control task can be examined with a simple application of the crossover model of manual control.[5] As shown in Fig. 7, the manual control loop consists

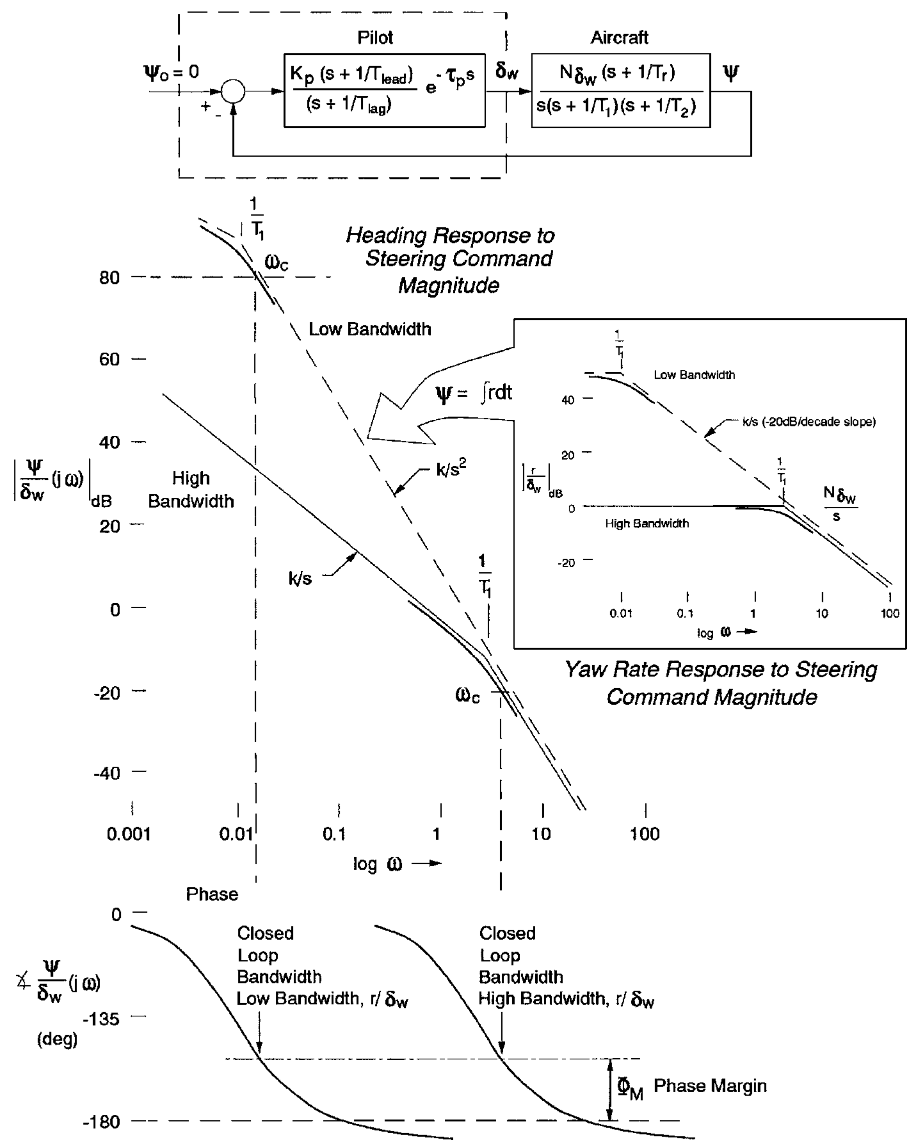

Fig. 7 Manual control of yaw attitude.

of a yaw attitude angle ψ feedback to a pilot capable of generating lead $(1/T_{\text{lead}})$ and lag $(1/T_{\text{lag}})$ compensation. In this analysis, yaw attitude is the integral of yaw rate. Thus, the flat shelf within the bandwidth of the yaw rate to steering command frequency response corresponds to a k/s-like region in the yaw attitude frequency response, where k is the pilot–vehicle system gain. This is an ideal characteristic for the yaw attitude loop closure providing the k/s-like region extends to sufficiently high frequency, that is, the yaw rate command bandwidth is high enough. The bandwidth is considered high enough when the pilot can close the loop with acceptable phase margin at a crossover frequency ω_c that is sufficiently high to ensure good regulation of yaw attitude. The low-yaw-rate bandwidth case (dashed lines representing an oversteer aircraft near the critical speed) implies that the pilot will not be able to achieve the necessary closed-loop bandwidth for good regulation or command following. Furthermore, the pilot's attempt to close the loop is likely to lead to instability (negative phase margin) and a category I PIO as defined in Ref. 6. Pilots are capable of compensating for low bandwidth, up to a point, by effectively placing their lead $(1/T_{\text{lead}})$ on top of the dominant aircraft pole $(1/T_1)$. Near the critical speed, the lead time required of the pilot (T_{lead}) would be unattainable. This is the situation corresponding to the 80–40 kn region of Fig. 6.

Conclusions

The understeer gradient UG (or equivalently the stability factor K) of the Navy trainer varies significantly with speed during rollout. Just after touchdown the aircraft may be slightly understeer, but UG decreases with speed becoming oversteer at roughly 80 kn. From roughly 80 to 40 kn, the UG variation is such that it remains close to the stability (critical speed) boundary. Thus, the yaw rate command bandwidth remains minimal in this speed range. This adverse handling characteristic is the primary manual control problem, not instability per se. Below 40 kn the yaw rate command characteristic becomes increasingly stable even as it becomes increasingly oversteer, and, thus, stability and control ceases to be a problem. In lieu of a tire redesign, the ground handling deficiencies can be alleviated with a simple yaw rate to nose wheel steering feedback system. The gain of the yaw rate feedback can be used to set the yaw attitude bandwidth as desired within the limitations of the system hardware.

Acknowledgments

Systems Technology, Inc., conducted the work presented herein under contract to The Boeing Company. This 15-month program featured direct participation of both Boeing and Navy technical personnel. The principal technical representative from the Navy was Marge Draper-Donley of Naval Air Systems Command. Robert Daugherty of NASA Langley Research Center provided the initial tire test data. A more complete tire test data set was later provided by Veridian under contract to Boeing.

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