Direct Side Force Control for STOL Crosswind Landings

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The Total In-Flight Simulator (TIFS) airplane was used to investigate the application of direct side force control (DSFC) to alleviate the crosswind landing problem. The TIFS airplane was configured to simulate the characteristics of a Class II STOL aircraft for these tests. Fifty-four evaluations were accomplished, including the first demonstration of the use of DSFC to perform wings-level crosswind landings. It was concluded that DSFC significantly improved the pilot's ability to perform a crosswind landing and was particularly beneficial when the basic airplane exhibited degraded flying qualities.

Introduction

LANDING an aircraft in a crosswind is a precise task in which the airplane flight path must be coincident with the runway centerline and the aircraft heading aligned with the runway while overcoming the lateral velocity or drift due to the crosswind. This lateral-directional task must be performed while the pilot also is concerned with precise height, airspeed, and pitch attitude control during the flare maneuver.

The pilot generally has two methods available for coping with the crosswind. He may either approach the runway with a crab angle and align the aircraft heading using rudder and aileron just prior to the touchdown (a crabbed approach) or sideslip the airplane with the upwind wing low and touch down on the upwind wheel first (a sideslipping approach). Pilots of conventional airplanes have adopted a combination of the two techniques. A crabbed approach is used until the aircraft is on a short final approach, at which time the nose is rotated to align the aircraft with the runway and the aircraft is landed wing down with a steady sideslip into the wind. If the pilot had direct control of side force, he might have the capability of handling most crosswinds with the wings level. For more severe crosswinds, where over-all DSFC capability might be exceeded, the magnitude of the bank angle required to balance the side force due to sideslip would be reduced.

To investigate the application of direct side force control during the crosswind landing task, a flight test program[1] was conducted in the USAF Total In-Flight Simulator (TIFS) aircraft.[2] The objectives of the program were to evaluate the usefulness of direct side force control during STOL crosswind landings, and to define parameters associated with the use of direct side force control which would increase pilot performance or decrease pilot workload. Investigation of the type of cockpit controller and mechanization scheme for use with direct side force control was also an important aspect of the program.

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Flight Test Program

Parameters Varied

It was necessary to select those parameters which would be expected to have the greatest effect on the generation of side force during crosswind landings and which would also have the greatest influence on the ability of the pilot to perform the crosswind landing. From the steady-state lateral-directional equations written in body axes with the simplifying assumptions that the side force and yawing moment due to aileron deflection, $Y(\delta_a)$ and $N(\delta_a)$, are zero, and with the small angle assumption, it can be shown that the bank angle per unit crosswind component, ϕ/v_{cw}, is

$$\phi/v_{cw} = 1/g[-Y_\beta + Y_{\delta_r}(N_\beta/N_{\delta_r})] \tag{1}$$

Equation (1) shows that the bank angle required for a sideslipping crosswind landing is largely a function of the directional stiffness of the airplane, N_β, the side force due to sideslip, Y_β, and the side force and yawing moment due to rudder deflection, $Y(\delta_r)$ and $N(\delta_r)$, respectively. However, to land with zero bank angle and without a crab angle in a crosswind, it is necessary to provide independent direct side force control. If the steady-state lateral-directional equations are written with the introduction of a third controller, the necessary side force control power can be determined. If δ_y is the side force generator deflection and $Y(\delta_y)$ the side force per unit generator deflection, solution of the steady-state lateral-directional equations yields

$$Y_{\delta_y}\delta_y = v_{cw}/V_o[-Y_\beta + Y_{\delta_r}(N_\beta/N_{\delta_r})] \tag{2}$$

Combining Eqs. (1) and (2) and solving for $Y(\delta_y)\delta_y$:

$$Y_{\delta_y}\delta_y = (g/V_o) \tag{3}$$

where V_o is the true speed and ϕ is the bank angle that would be necessary in a conventional sideslipping crosswind landing. Hence, if the bank angle required to land a given airplane in a given crosswind is known, then the necessary side force control power for a wings-level crosswind landing is known. Therefore, the parameters which determine the necessary side force using independent side force control are Y_β, $Y(\delta_r)$, N_β, and $N(\delta_r)$.

Equation (2) implies that part of the side force is obtained by rudder deflection, but the contribution due to rudder deflection is the same for conventional wing-down sideslipping approaches or wings-level crosswind approaches with independent side force control, as can be seen by comparing Eqs. (1) and (2).

In conventional crosswind landings, the pilot develops side force through bank angle and from the force resulting from the rudder deflection required to maintain proper aircraft heading. Because of the steady-state sideslip and positive effective dihedral (L_β negative), he must maintain steady-state aileron forces to prevent the airplane from rolling out of the wing-low attitude. Steady rudder forces, providing positive directional stability, are of course required to prevent the airplane from weathercocking into the resultant relative wind. Side force at the vertical tail is a by-product of maintaining the proper heading with the rudder. Superimposed on the steady aileron and rudder forces are the continuous transient aileron and rudder inputs which the pilot must make, especially near the ground, to counter turbulence upsets and wind shear which excite the lateral-directional dynamic modes of motion. If the pilot has a separate controller for pure independent side force control, then he must still counter the rolling and yawing due to sideslip in the conventional way by holding steady aileron and rudder forces. Hence, rather than reduce workload, this approach to side force control may simply introduce to the pilot an additional controller from which he may derive little benefit and it may, as a result, even increase his workload. With aileron-to-side-force and rudder-to-side-force interconnects or crossfeeds, the pilot would have to contend with transients (the nature of which depend on lateral-directional dynamics) but would not have to maintain steady-state aileron and rudder forces during a crosswind landing. Therefore, his workload should be reduced and his performance improved during the crosswind landing task. Proper compensation for the aileron and rudder signals which result from the interconnects with DSFC commands may be necessary to minimize excitation of the lateral-directional modes of motion when the pilot makes DSFC inputs. In this investigation, aileron- and rudder-to-side-force crossfeed was used for all DSFC configurations. The aileron and rudder deflection for a steady-state sideslip, with or without pure independent side force control, can be determined from the steady-state lateral-directional equations. The aileron deflection, δ_a, is

$$\delta_a = v_{cw}/V_o[(N_{\delta_r}L_\beta - L_{\delta_r}N_\beta)/(L_{\delta_r}N_{\delta_a} - N_{\delta_r}L_{\delta_a})] \quad (4)$$

and likewise for the rudder deflection

$$\delta_r = v_{cw}/V_o[(L_{\delta_a}N_\beta - N_{\delta_a}L_\beta)/(L_{\delta_r}N_{\delta_a} - N_{\delta_r}L_{\delta_a})] \quad (5)$$

where $L(\delta_r)$ and $L(\delta_a)$are the rolling moments due to rudder and aileron deflection, respectively. Equations (4) and (5) indicate that L_β is also an important parameter in determining the amount of aileron control required to perform a crosswind landing and hence is an important factor in pilot workload.

It has been shown above that the stability derivatives of concern in steady-state sideslipping conditions, as in a crosswind landing, are Y_β, N_β, and L_β. The rudder control derivatives, $Y(\delta_r)$ and $N(\delta_r)$, are also quite significant in the determination of side force control power. The lateral-directional dynamic parameters which influence the pilot's ability to execute a crosswind landing were shown[3] to be the Dutch roll damping ratio, ζ_d, the roll-to-sideslip ratio in the Dutch roll, $|\phi/\beta|_d$, and the roll mode time constant, τ_R.

Previous studies of lateral-directional dynamics[4] have shown that ζ_d is a function of Y_β, N_β, and L_β, as well as N_r and other lateral-directional derivatives. The roll-to-sideslip ratio is also a function of these derivatives and has been shown to vary as a rough approximation of the ratio $|L_\beta/N_\beta|$. Hence, the dynamic modal parameters of interest in crosswind landings are strongly related to the stability derivatives of concern in steady-state sideslipping conditions.

Table 1 Evaluation configuration identification

$N_\beta \frac{1}{\text{sec}^2\text{rad}}$	0.94		0.42	
$L_\beta \frac{1}{\text{sec}^2\text{rad}}$	−1.57	−2.95	−1.57	−2.95
$\phi/v_{cw} = 0.21 \frac{\text{deg}}{\text{fps}}$	1	2	3	4
$\phi/v_{cw} = 0.31 \frac{\text{deg}}{\text{fps}}$	5	6	7	8
$\phi/v_{cw} = 0.42 \frac{\text{deg}}{\text{fps}}$	9	10	11	12

Therefore, L_β and N_β were chosen as two of the parameters for investigation in this experiment. The third variable chosen for investigation was the ratio of bank angle to unit crosswind component, ϕ/v_{cw}, directly, rather than Y_β. The bank angle may be important as a visually apparent parameter to the pilot. Also, the side force required for a wings-level crosswind landing is directly proportional to the bank angle required in a conventional crosswind landing. Since ϕ/v_{cw} is a function of Y_β, L_β, and N_β, the value of Y_β was varied as necessary to keep ϕ/v_{cw} at the desired value as L_β and N_β were varied.

The simulated vehicle was selected to conform to the landing approach configuration of a Class II STOL as defined by MIL-F-83300. Dimensional derivatives, both longitudinal and lateral-directional, were collected from available data of proposed and existing Class II STOL airplanes. These data were analyzed to obtain a set of composite derivatives to represent the basic STOL vehicle to be simulated in the landing approach Flight Phase.[1] Variations for evaluation were then made in the parameters ϕ/v_{cw}, L_β, and N_β, resulting in twelve evaluation configurations as shown in Table 1. The numerals in the matrix of Table 1 identify the twelve configurations evaluated. All other lateral-directional and longitudinal derivatives were held constant throughout the investigation.

DSFC Mechanizations

Two modes of direct side force control were mechanized. One was a manual system where the pilot controlled the side force input through the thumb-wheel controller. A schematic of the manual DSFC is shown in Fig. 1. The three simultaneous control surface inputs from a single controller resulted in a wings-level, steady-state sideslip.

Because there was no previous experience or data on the cockpit location or on desirable types of DSFC cockpit controllers, two were installed. One controller was located integral to the number one power lever knob, the other

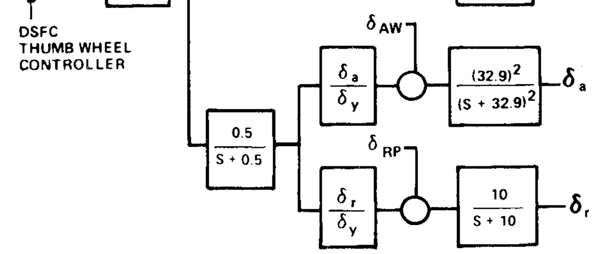

Fig. 1 Manual DSFC mechanization.

was located to the left side of the pilot's aileron control wheel. In this way, the pilot could use the controller of his choice—the one that was most efficient and most convenient for the task. Further, the most desirable of the two locations could then be determined during the course of the investigation.

The second mode of DSFC mechanized was an automatic system which relieved the pilot of all but longitudinal control of the airplane. This system maintained the airplane on ILS localizer course with the wings level and without crab angle in a crosswind. Figure 2 shows a block diagram of the automatic system mechanization. Since the TIFS was used in the model-following mode, the responses of the model and the TIFS were essentially the same. Therefore, the transfer function of the model-following loops and the TIFS can be considered to be unity. Bank angle, ϕ_m, roll rate, p_m, localizer error, and heading error, $\epsilon(\psi)$, signals were used as input commands. The bank angle stabilization loop maintained a wings-level attitude throughout the approach. Damping in the roll axis was achieved through roll rate feedback. Provision was made for the pilot to superimpose a bank angle command through the bank angle stabilization loop using aileron wheel inputs, δ_{AW}.

The localizer error signal was used to drive the side force generators to maintain the airplane on an extended runway centerline. The integral of the localizer error signal was included to eliminate steady-state localizer errors. Damping of the side force loop was achieved through a localizer rate signal.

The heading angle stabilization loop maintained the airplane heading coincident with runway direction. The TIFS flight director was used to provide an error signal which was the difference between the airplane heading and the landing runway direction, $\epsilon(\psi)$. In this control loop, a small amount of localizer error signal was used to rotate the airplane heading towards the centerline when a localizer error existed. For example, if the airplane was to the right of centerline, the heading was automatically corrected to the left a maximum of 2.5°. Using rudder pedal inputs, δ_{RP}, the pilot could superimpose a change in airplane heading through the heading stabilization loop.

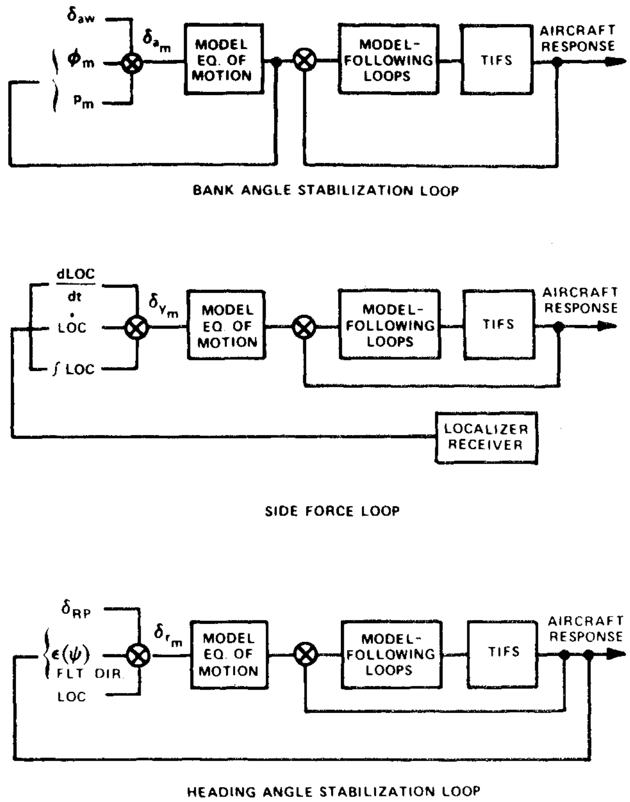

Fig. 2 Block diagram of automatic DSFC mechanization.

In-Flight Evaluations

The various configurations were evaluated by two engineering test pilots. Each configuration was evaluated first with no DSFC, then with the manual mode of DSFC, and finally, with the automatic mode of DSFC. An over-all pilot rating was assigned by the pilot after each evaluation in accordance with the Cooper-Harper rating scale.[5]

The task evaluated was the VFR landing approach with a constant 15-knot crosswind component. Three successive VFR landing approaches, including the flare maneuver and simulated touchdown, were accomplished for each evaluation. Two of the approaches were flown with turbulence inputs to the model computer so that the pilot could assess the effect of a turbulent environment. At a predetermined touchdown height, the pilot would receive a visual and aural touchdown signal. The constant 15-knot crosswind component was obtained through a combination of natural wind and simulated wind[1] obtained through the TIFS side force capability. The TIFS airplane was flown at a final approach speed of 130 KIAS and a flight path angle of $\gamma = 6°$; however, the evaluation pilot was flying an airplane with the characteristics of a medium-weight STOL transport at an 80-knot final approach speed.

Discussion and Results

The configuration change on a given evaluation flight was from no DSFC to manual to automatic. In this way, a direct comparison of the differing modes of DSFC was obtained for each dynamic configuration simulated.

Over-all, 54 evaluations were accomplished: 21 with no DSFC, 20 with manual DSFC, and 13 with automatic DSFC. Of the 21 evaluations with no DSFC, eight received a pilot rating of $PR = 4$ or better. With manual DSFC, 17 of the 20 evaluations resulted in $PR = 4$ or better, and with the automatic system, 11 of the 13 evaluations resulted in pilot rating of $PR = 4$ or better.

Data collected during the evaluations included pilot comments and ratings and time histories of airplane state parameters and pilot control inputs, including pilot usage of the DSFC feature. During the automatic system evaluations, DSFC activity and localizer error were also recorded. Pilot comments and ratings were recorded using onboard voice recorders, while all other data were recorded on the onboard, 58-channel digital tape recorder. Although the pilot was evaluating the over-all task, it became obvious during the conduct of the experiment that he based most of his opinion on the flare maneuver and simulated touchdown. To represent the actual conditions with which the pilot was confronted during this critical phase, it was necessary to limit the time increment for data extraction usually to the 10–20 sec prior to touchdown. It was during this short time period that the pilot was attempting to establish a steady-state sideslip with bank angle, when not using DSFC for the crosswind landings, and only during this time was it necessary for him to hold large steady control forces. The mean sideslip during the 10–20 sec period prior to touchdown was used as an indicator of performance.

It is important to note that refinements in the development of the automatic system continued during the evaluation program. It is reasonable, therefore, to expect that changes made in the system affected pilot rating. Some of the earlier evaluations of the automatic system suffered as a result, with ratings improving as system improvements were accomplished.

Manual Direct Side Force Controller

Some important results of this investigation concerned the manual DSFC controller per se. Since there was no a priori knowledge of the best location for the controller, both were installed in parallel and remained in the airplane throughout the evaluation program so that the pilot could use the controller location of his choice. The intent of providing the evaluation pilot with the above option was to minimize possible adverse opinions of DSFC because of an inconvenient controller location.

The proportional side force controllers were provided with a center detent so that the pilot could ascertain the zero side force position. Total authority of the controllers was determined so as to provide enough sideslip to counter a 15-knot direct crosswind for the configurations with the highest values of the side force derivative Y_β, and the higher value of the directional stiffness, N_β. Hence, total authority was not required for the configurations with the lower values of Y_β.

Originally, the side force control was direct in that a pilot thumb movement to the right, or clockwise on the power-lever-mounted controller, provided positive sideslip or drift to the right. In this way, if the pilot sensed drift to the left, the drift could be arrested with application of direct side force to the right. It was soon realized, however, that on the final approach, where the pilot is concerned with assessing the effects of crosswind, his primary cue is crab angle relative to the runway, not side velocity or drift. The pilot, in seeing a crab angle to the left (nose left of runway centerline) would have to apply side force to the left when he wanted the nose of the airplane to move right for proper runway alignment. This often would lead to his applying side force in the wrong direction. Since the pilot wanted the nose to move right, his reaction was to deflect the side force controller to the right. Therefore, after the first evaluation flight, the side force controllers were modified so that right deflection of the controller produced left sideslip or negative side force. This controller sense was maintained through the remainder of the evaluation program, and proved to be satisfactory.

The pilots found that they most naturally used the side force controller mounted on the power lever. During the landing approach and landing, the pilot normally flies with one hand on the power lever anyway, and to perform the additional task of side force control with the "power lever hand" was not difficult. The pilots' objection to the control-wheel-mounted side force controller was the additional control task for an already "busy" left thumb. The controller was placed adjacent to the aileron-elevator trim switch so that the side force controller, the aileron-elevator trim control, and the interphone-radio transmit switch were all within the arc of the thumb when the pilot gripped the control wheel with his left hand. On several occasions, the evaluation pilot inadvertently made a side force input when intending to make an aileron trim correction or he attempted to make side force inputs with the trim control. The three closely located controls proved to burden the pilot in that he had to make a conscientious effort to reach for the proper controller when his attention was directed at the precise tasks of landing approach, flare, and touchdown.

Both pilots experienced some difficulty in establishing the required amount of side force control to use, especially when flying in turbulence. This was partly due to the variations in the natural wind as altitude was reduced on final approach. Also, precise final adjustment of the side force control required that any crab angle or side velocity be sensed precisely, which again was a problem with turbulence-induced oscillations of the airplane present. Side velocity is easily sensed in the flare, but both pilots preferred, at that point, to stop the side velocity by conventional aileron and rudder techniques rather than try to take into account the effects of an additional controller during the flare and touchdown. On occasion, it was noticed that there was some overcontrol of side force, resulting in the pilots having to cope with an effective crosswind from the direction opposite to that for which he had corrected. Therefore, as mechanized in this investigation, manual DSFC was used to establish the airplane in a trimmed, wings-level, steady-state sideslip condition. Normal aileron and rudder control techniques were then used to make small corrections about the established steady-state condition.

Comparison of Results with and without DSFC

For purposes of discussion and comparison, the twelve configurations shown in Table 1 were divided into four groups of three configurations each. The configurations within each group have in common their values of L_β and N_β, so that each group represents one of the four combinations of the two values of L_β and N_β. The variable among the configurations of each group is ϕ/v_{cw} and, therefore, Y_β. Control derivatives were held constant throughout the experiment. Values of the control derivatives were selected from available data for proposed and existing medium-weight STOL transport airplanes. Con-

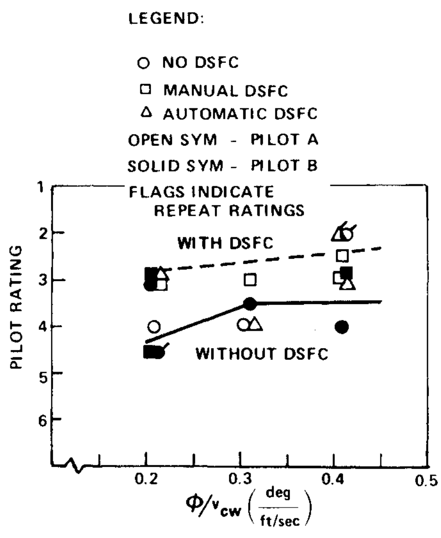

Fig. 3 Effect of DSFC on configurations 1, 5, and 9 with $N_\beta = 0.94$ and $L_\beta = -1.57$.

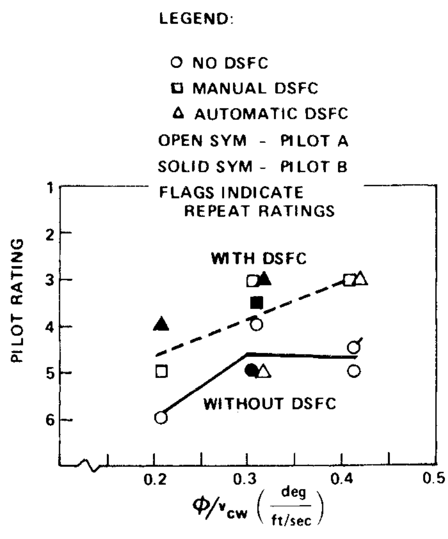

Fig. 4 Effect of DSFC on configurations 2, 6, and 10 with $N_\beta = 0.94$ and $L_\beta = -2.95$.

trol force gradients and breakout forces for the elevator, aileron, and rudder were initially set at the maximum recommended values,[6] but the over-all control sensitivity was selected by the evaluation pilot during pre-evaluation practice flights. The actual values used are presented in Ref. 1.

In general, the over-all handling qualities for the crosswind landing task improved when the pilot had the use of either the manual or the automatic mode of DSFC, as opposed to having no DSFC. The degree of improvement was, however, a function of the lateral-directional characteristics of each configuration. The incremental improvement in the pilot ratings was usually 1–1.5 with the exception of configurations with the lower N_β and higher L_β, where pilot ratings improved from $PR = 7$ to $PR = 3$. Note that, in most instances, the improvement in pilot rating crossed a major boundary on the rating scale. For example, the use of DSFC changed the pilot rating from "deficiencies warrant improvement" to "satisfactory without improvement." Comparisons of the results obtained with and without DSFC are shown on Figs. 3–6.

Crosswind Landings without DSFC

The evaluation pilot was free to use the crosswind landing technique of his choice. Both pilots used a crabbed final approach and converted to a wing-low steady sideslip just prior to the flare. The airplane was maintained in the steady sideslip through the flare and touchdown. Neither pilot elected to attempt a crabbed flare and to decrab the airplane just prior to touchdown. Many of the problems encountered with the sideslipping crosswind landing technique were common to all configurations evaluated. The most common complaint or difficulty was the large force required on both the aileron wheel and rudder pedals to effect the crosswind landing even though control force gradients and overall control sensitivity had been carefully selected. The presence of turbulence tended to aggravate the problem of heavy control forces since the pilot had to superimpose forces of a transient nature on the already large steady forces in order to suppress the responses of the airplane to turbulence. Large lateral forces also reduced the precision of longitudinal control and sometimes resulted in longitudinal oscillations when the pilot was attempting to establish a steady-state sideslip for the crosswind landings.

The least difficulty was experienced for the group of configurations with the smaller effective dihedral (lower L_β) and highest directional stiffness (higher N_β). The parameter ϕ/v_{cw} didn't make much difference for these configurations. For the remaining configurations, however, low values of ϕ/v_{cw} were associated with low Dutch roll damping ratio for an unaugmented airframe. As a result, the pilot encountered crosswind landing difficulties because of the easily excited lateral-directional oscillations. The poorest combination of parameters for crosswind landing was the higher L_β, lower N_β, which produced both bank angle and directional control difficulties. Low ϕ/v_{cw} in this case resulted in poor Dutch roll damping, while the higher ϕ/v_{cw} increased the aileron input required to complete the crosswind landing.

Crosswind Landing with Manual DSFC

Using the manual DSFC feature, the over-all pilot rating for the crosswind landing task improved in nearly every case. Of course, the pilot technique also changed. With DSFC, the airplane was flown in a wings-level sideslip so that the pilot's perspective of the runway was the same that he would see with no crosswind. When DSFC inputs were made by the pilot, the aileron-, and rudder-to-side-force command crossfeed feature provided the required aileron and rudder trim for a steady-state sideslip condition with the wings level and no turn rate. This feature, therefore, provided the capability for the pilot to fly the airplane as though there were essentially no crosswind. That is, he could perform the final approach, flare, and touchdown with the wings level and the airplane heading aligned with the runway while the DSFC feature maintained the airplane in a sideslip to counter the crosswind.

The pilot's technique was to use the crab angle on final approach to assess the crosswind. The DSFC controller was then used to eliminate the crab angle. As the airplane progressed along the final approach, some iteration of the DSFC was used to account for changing wind conditions as altitude changed.

The use of DSFC strongly alleviated most of the problems that were encountered without DSFC. It did not, of course, eliminate all the pilot's problems in the crosswind landing task. For example, poor lateral-directional dynamics were still poor when the pilot had the use of DSFC. However, the pilot was better able to contend with the case of poor dynamics when using DSFC because the task of establishing a wing-low steady-state sideslip was

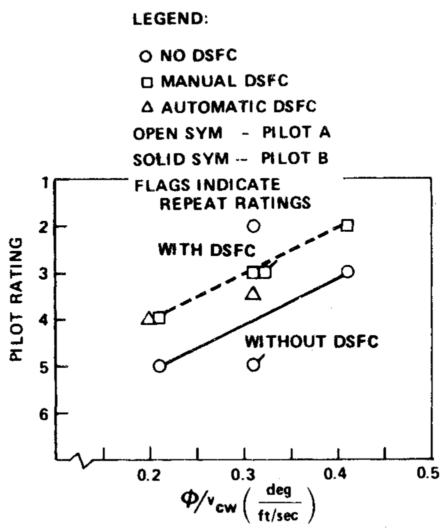

Fig. 5 Effect of DSFC on configurations 3, 7, and 11 with $N_\beta = 0.42$ and $L_\beta = -1.57$.

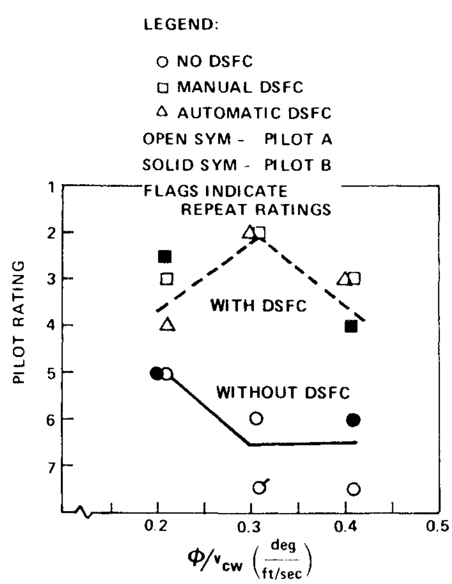

Fig. 6 Effect of DSFC on configurations 4, 8, and 12 with $N_\beta = 0.42$ and $L_\beta = -2.95$.

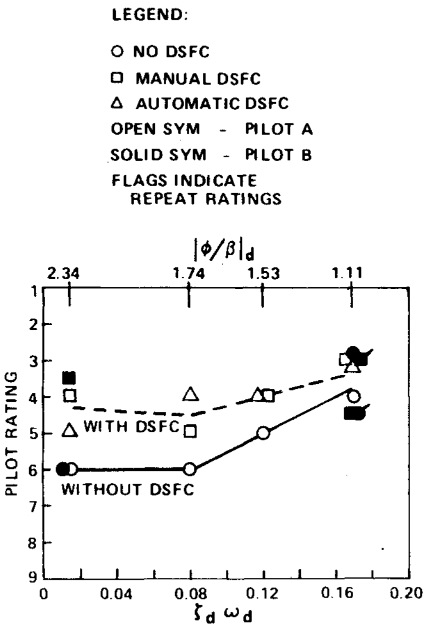

Fig. 7 Pilot ratings vs total Dutch roll damping for configurations with $\phi/v_{cw} = 0.21$.

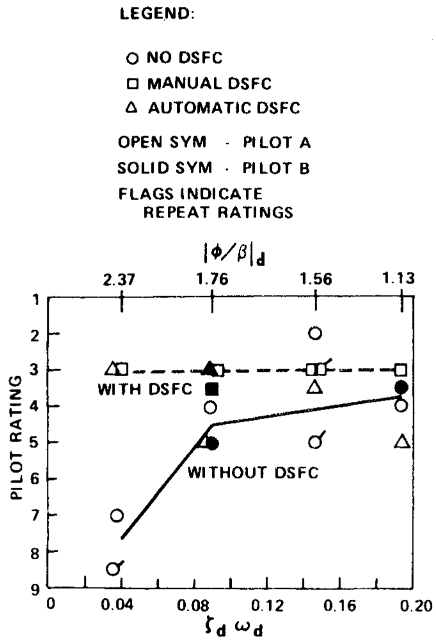

Fig. 8 Pilot rating vs total Dutch roll damping for configurations with $\phi/v_{cw} = 0.31$.

essentially eliminated and more attention could be devoted to other aspects of the landing approach task.

Aileron and rudder control forces were considerably reduced when using DSFC. The elimination of the wing-down steady sideslip requirement reduced the heading alignment problem that was encountered with most configurations. As a result, the pilot was able to devote more of his attention to suppressing the turbulence-induced Dutch roll oscillations. Further, there was less excitation of the lateral-directional modes from control inputs because the pilot did not have to convert the crab angle established on final approach to a steady sideslip for landing. It was noted that, when using DSFC, the rms value of control inputs about the mean force level often increased above the no-DSFC case, indicating that the pilot was able to devote more effort to suppressing lateral-directional oscillations because he was working about a lower mean-force level. Since the pilot controls aileron and elevator with one hand during landing, with the other hand devoted to power control, heavy forces in one axis (the ailerons in this case) reduce the precision with which small force changes can be applied in another axis, the elevator. The reduction of aileron forces when using DSFC improved the precision of longitudinal control and both pilots commented that any previous tendency to a pilot-induced oscillation during the flare was reduced.

Automatic Direct Side Force Control

To use the automatic system, the pilot manually flew the airplane until it was on the final approach course and heading and in a position to commence the descent to landing. At this point, the automatic system was activated by an engage switch on the number one power lever. After the system was engaged, the pilot's task was reduced to longitudinal control of the airplane. The automatic DSFC system maintained the airplane on the ILS localizer course with the wings level and the heading aligned with the runway heading. There was one major objection to the operation of the automatic DSFC system. Lateral accelerations of $n_y = \pm 0.10\ g$ were experienced on the automatic approaches. Occasional lateral accelerations of $n_y = \pm 0.15\ g$ were experienced. The lateral acceleration was a result of the inherent irregularities in the localizer signal that are common to many VHF ILS localizer installations. Filtering the ILS error signal eliminated small, high-frequency variations, but large, sharp irregularities could not be eliminated with filtering alone. Even with the difficulties experienced, the automatic DSFC system did counteract the crosswind, maintain runway heading, and position the airplane over the runway with the wings level. The pilot was, therefore, completely relieved of the lateral-directional control task.

For automatic DSFC to be completely successful, the bothersome lateral accelerations must be reduced or eliminated. This may depend on the availability of a better localizer signal and/or on the use of inertial signals to the automatic pilot system to smooth the transient motions of the airplane.[7]

Effects of Lateral-Directional Dynamics

In view of the many pilot comments about Dutch roll damping and the response of the various configurations to turbulence, it appeared desirable to plot pilot rating both with and without DSFC as a function of Dutch roll damping (Figs. 7-9). It must be remembered, however, that because of the way derivatives were varied in this program, each change in L_β or N_β caused changes in all the lateral-directional modal parameters. Also, changes in ϕ/v_{cw} through the derivative Y_β caused changes in Dutch roll damping. For example, an increase in L_β primarily causes $|\phi/\beta|_d$ to increase and ζ_d to decrease. A decrease in N_β primarily causes the Dutch roll frequency, ω_d, to decrease and $|\phi/\beta|_d$ to increase. Therefore, in interpreting Figs. 7-9, it should be noted that as $\zeta_d\omega_d$ decreased, $|\phi/\beta|_d$ increased. The $|\phi/\beta|_d$ values for each configuration are shown on the figures.

All three plots, for the three values of ϕ/v_{cw} investigated in this experiment, show a tendency for pilot rating for evaluations without DSFC to become worse with decreasing $\zeta_d\omega_d$. This, of course, is not an unexpected result. In all cases, however, pilot rating for evaluations with DSFC decreased much less with $\zeta_d\omega_d$. For the medium ϕ/v_{cw} cases, the pilot rating for evaluations with DSFC was essentially invariant with decreasing $\zeta_d\omega_d$. These plots point out that the greatest benefits from DSFC in the crosswind landing task were obtained for configurations with the least desirable lateral-directional handling

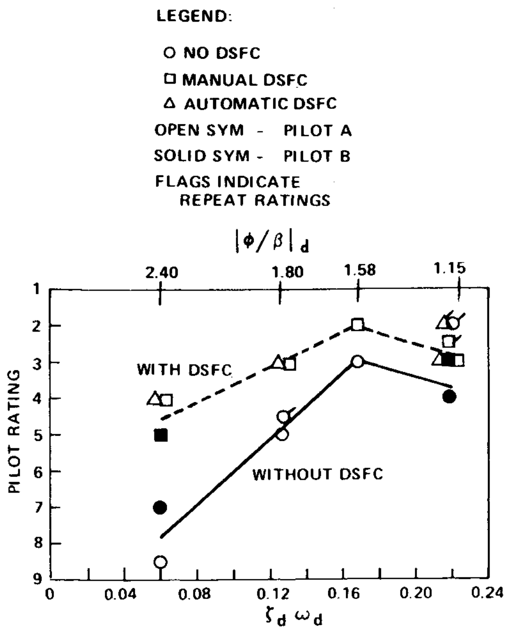

Fig. 9 Pilot rating vs total Dutch roll damping for configurations with ϕ/v_{cw} = 0.42.

qualities. That is, configurations which received the poorest pilot ratings without DSFC showed the greatest improvement in terms of an incremental improvement in the numerical pilot rating when the pilot had the aid of DSFC. Configurations which were reasonably good without DSFC were improved to a lesser degree, but this improvement may be important since, on several occasions, the use of DSFC raised the airplane from the "deficiencies warrant improvement" category to the "satisfactory without improvement" category.

Control Power and Pilot Control Forces Used

To determine the roll control power and yaw control power actually used by the pilot, the aileron and rudder deflections were recorded during the crosswind approaches and landings performed in this investigation. The side force generator, aileron, and rudder deflections required or the steady-state side-slipping crosswind landing condition could easily be determined from Eqs. (2, 4, and 5). However, control power values determined from these expressions would not account for the magnitude of control power that the pilot actually needed and used to cope with the turbulence and wind environment in which the evaluations were conducted. Table 2 shows the values of control power used by the pilot during one evaluation of each configuration. The pilots' mean and maximum aileron wheel and rudder pedal force inputs used are also shown so that the forces can be compared for the cases with and without DSFC. When the pilot used DSFC, the δ_a/δ_y and δ_r/δ_y crossfeeds provided sufficient aileron and rudder deflection to counter steady-state rolling and yawing moments.

The control deflections used to determine control power were essentially the maximum value used by the pilot in performing the crosswind landing task, including the aileron and rudder deflections resulting from the δ_a/δ_y and δ_r/δ_y interconnects. These maximum values of aileron and rudder deflection were taken from probability density distributions. The actual values used to compute the control power were control surface deflections for which the probability of exceeding was 0.02. The pilots' maximum force inputs were also obtained from probability density distributions using values for which the probability of exceeding was 0.02.

The mean sideslip attained during the landing flare maneuver and touchdown also is shown in Table 2. The control surface deflections required, and therefore, the control power are a function of sideslip β. If the pilot, in performing the crosswind landing, exactly counters the existing crosswind with a zero crab angle, then $\beta = v_{cw}/$

Table 2 Control power and forces used by the pilot

Conf. no.	P.R.	Sideslip attained, deg	F_{AW} (lb) Mean	F_{AW} (lb) Max	Roll control power, deg/sec²	F_{RP} (lb) Mean	F_{RP} (lb) Max	Yaw control power, deg/sec²	Y/W
1N[a]	4	3.5	3.4	6.8	6.6	34	43	4.2	
1M[b]	3	8.4	0.96	7.5	14.6	20	28	10.3	0.122
5N	4	4.2	4.85	10.0	10.6	35	54	5.2	
5M	3	3.8	0.81	7.5	9.9	8.6	18	5.0	0.169
9N	8	4.6	5.9	11.0	8.4	40	63	6.7	
9M	3	7.5	1.8	9.5	13.2	9.8	40	10.7	0.213
2N	6	5.4	9.5	12.0	13.8	53	66	7.1	
2M	5	6.3	3.9	9.0	16.0	15	26	6.9	0.125
6N	5	6.0	12.6	15.0	16.2	66	76	8.0	
6M	3½	7.2	3.0	8.0	17.3	18	29	7.9	0.172
10N	5	2.3	6.8	14.0	14.1	30	52	5.5	
10M	3	8.0	2.5	8.5	24.6	8.0	20	10.5	0.216
3N	5	4.5	4.5	8.5	9.5	24	42	4.1	
3M	4	4.3	0.5	6.8	10.9	5.1	15	3.3	0.107
7N	5	2.0	2.7	11.5	12.4	19	36	3.2	
7M	3	6.8	0.5	8.0	15.1	10	18	4.9	0.152
11N	3	3.8	7.0	9.0	9.4	22	34	3.2	
11M	2	4.9	4.2	8.5	9.9	17	22	3.0	0.197
4N	6	2.6	6.0	15	12.4	22	42	4.1	
4M	4	3.6	0.5	9.5	14.1	0.1	26	3.9	0.109
8N	7	3.5	11.5	15	13.0	23	37	3.8	
8M	3	5.0	1.9	6.5	15.7	3.8	16	3.0	0.155
12N	8½	3.6	11.9	17.7	16.0	26	44	4.3	
12M	4	6.2	1.0	7.7	16.2	2.4	14	4.6	0.200

[a] N: No DSFC. [b] M: Man DSFC.

V_0 within the limits of the small-angle approximation. Therefore, sideslip can be considered as an approximate measure of how well the pilot performed the crosswind landing in this experiment. When comparing and assessing the control power values shown, therefore, the sideslip attained must be considered.

It can be seen from Table 2 that, with the aid of DSFC, the pilot generally attained a larger sideslip during the flare and landing than was attained without DSFC. Not only were larger sideslips achieved, but because of the aileron and rudder interconnects with side force control, smaller maximum aileron wheel and rudder pedal forces were used. If the crosswind component were always exactly 15 knots and the turbulence were always the same, and if the pilot had always landed with a zero crab angle relative to the runway, then a direct comparison of control power could be made for the cases with and without DSFC. The listed sideslip values and the pilot comments indicate that zero crab angle was not always achieved. Also, because the natural wind was often variable, the crosswind during the flare and touchdown may have been different from 15 knots. However, comparisons of configurations in which similar values of sideslip were attained with and without DSFC indicate that the use of side forces does not result in any reduction of roll or yaw control power for the crosswind landing task. Actually, if sideslip is considered indicative of pilot performance, then better performance was generally achieved when the pilot had the aid of DSFC. This better performance was achieved with smaller pilot control force inputs, but also resulted in more control power being used. The fact that the pilot was able to achieve better performance (larger sideslip in the crosswind) with less effort (smaller control forces) resulted in better pilot ratings generally when the pilot was able to use DSFC.

To put the required side force control power into perspective, the side force required to develop 6.5° of sideslip for the configurations evaluated in this investigation was calculated. The rudder deflection was also determined. From the $Y(\delta_v)\delta_v$ and $Y(\delta_r)\delta_r$ values so obtained, the total side force in pounds was determined and ratioed to the weight of the 130,000-lb model used in this investigation. The values of Y/W obtained are listed in Table 2. The tabulated values show that, depending on the basic side force characteristics of the airplane (principally Y_β), magnitudes of generated side force necessary to counter a 15-knot crosswind with a final approach speed of 130 knots vary from approximately 10 to 20% of the airplane's lift in 1-g flight.

Conclusions

The capability to land wings-level in a 15-knot crosswind with a 130-knot final approach speed was demonstrated in this in-flight evaluation program. The availability of manual DSFC to the pilot made the wings-level landing in a crosswind possible and was found to improve the pilot rating obtained in the crosswind landing task. The degree of improvement in pilot rating was found to be largely determined by the basic airplane lateral-directional dynamics. Airplanes which received the best pilot rating without DSFC showed the smallest improvement in terms of incremental pilot rating when the pilot had the aid of DSFC. Airplanes which received the poorest pilot rating without DSFC showed the greatest improvement in terms of incremental pilot rating when evaluated with DSFC. The aileron wheel force required to maintain the steady banked side-slipping attitude was the most frequent pilot objection to all the configurations evaluated. With the use of DSFC, as mechanized in this experiment, the high forces were alleviated, and the pilot workload during the crosswind landing task was therefore reduced. Further studies are necessary to determine the best type of cockpit controller to be used and the optimum controller sensitivity. For example, in this program, a proportional controller was found to be satisfactory; however, a side force rate controller warrants investigation.

The effects of rolling moment and yawing moment due to side force generator deflection were not considered in this investigation, but they may have a significant effect on the utility of DSFC. If the side force generator design provides rolling moment to oppose the effective dihedral of the airplane, then some reduction in required roll control power may be realized when using DSFC.

Further development of the automatic DSFC should be undertaken to compensate for the irregularities in the VHF localizer signal. The use of inertial type signals[7] should be investigated as a means to eliminate the effect of these sharp bends in VHF localizer signals. Also, the incorporation of DSFC into fully automatic landing systems may offer attractive potential benefits.

Finally, for the crosswind landing task, an investigation with larger crosswind components and higher turbulence levels than those used in this investigation should be undertaken. This investigation has shown DSFC to be beneficial in a 15-knot crosswind, but it is important to determine if greater benefits could be realized in more severe crosswind and turbulence conditions. Further, it should be determined whether a pilot rating improvement results only from landing wings-level in a crosswind or whether merely reducing the required bank angle would be sufficient.

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