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Explanation of Poorly Damped Lateral Oscillations during Automatic Approach with Aileron Steering

By K. H. DOETSCH

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Explanation of Poorly Damped Lateral Oscillations during Automatic Approach with Aileron Steering

By K. H. DOETSCH

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April, 1958

Summary. Poorly damped Dutch-roll oscillations were experienced during landing approaches on different aircraft when controlled by an autopilot employing the aileron-steering technique. This phenomenon is explained with the aid of the time-vector representation and remedies are discussed.

1. Complaints have recently been made of poorly damped Dutch-roll oscillations of a number of civil and military transport aircraft, when automatically controlled by the aileron-steering technique. This symptom occurred not only on a swept-wing aircraft, where one would expect a large rolling moment due to yaw, but also on several, although not all, straight-wing aircraft. The swept-wing case has been investigated[1] and the cause of the trouble has been discovered. Means of alleviating it have also been explored, and they should be generally applicable.

Historically, the trouble is connected with the initiation of the present British method of automatically controlling an aircraft when flying along a radio beam. Early experience had shown that it was very difficult to achieve good signal patterns for approach beams. When flying an aircraft along such a distorted beam as exemplified in Fig. 1, it appeared unpromising to use the rate of beam deviation (short: beam rate) signal, $\dot{y}$, to damp the flight-path oscillation about the average beam centre-line, because of the varying gradient and even reversal of sign of the gradient of the signal strength.

Therefore the product of heading error and flight velocity, ψV, was, in this country, substituted for rate of beam deviation, $\dot{y}$. This is admissible if it can be assumed that the aircraft heading is identical with flight-path azimuth, *i.e.*, that there is no sideslip or variation of wind drift. This assumption appears justified for the long-period motion of the aircraft with respect to the beam. The repercussions of a control law based on this assumption on the short-period Dutch-roll oscillation were not fully appreciated at the time and led eventually to the recent spate of difficulties.

The problem has been investigated for a swept-wing aircraft on an analogue computer[1]. Fig. 2 in this paper is taken from Fig. 17, the relevant one, of Ref. 1. The term which is substituted for beam rate is contained, in the particular autopilot used, in the term $K_3\psi$ which contributes to the deflection of the platform and thereby to the demanded bank angle ϕ_D (this is in fact picked up as rate of bank

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* R.A.E. Tech. Note Aero. 2564, received 2nd June, 1958.

demand ϕ_D and equated to the rate of control application, $\dot{\xi}$. This is for our purpose equivalent to demanding aileron deflection, ξ, proportional to ϕ_D and therefore proportional to heading error ψ). It will be seen that as this so-called 'crossfeed' or 'aileron steering' term is increased, the long-term motion (period about 58 sec) is in fact being reduced but the shorter-period (about 9·8 sec) Dutch-roll oscillation becomes poorly damped. There was also evidence, at first sight paradoxical, of a decrease in the rolling moment due to sideslip leading to larger rolling amplitudes and poorer damping of the Dutch-roll oscillation.

Both phenomena have recently been explained, and means to combat the ensuing difficulties can now be discussed more rationally. Fig. 3a shows schematically the condition for the aircraft path oscillating with a long-period motion about the beam centre-line. A positive heading error leads, through the aileron steering, to a negative rolling moment in order to bank and steer the aircraft back onto the beam. The effect of sideslip can be neglected for this slow, long-period motion.

The same positive heading error, however, leads in the short-period case shown in Fig. 3b to a positive rolling moment because the error is almost exclusively sideslip which produces in the usual way, through dihedral and sweep effect, a positive rolling moment. At the same time the aileron steering term, which does not, of course, distinguish between a heading error due to sideslip or one due to change of flight-path direction, remains fully effective. Both these rolling moments, being of opposite sign or 'phase', partly cancel each other.

The effect on the Dutch-roll oscillation can best be studied with the time-vector representation. The polygons of the three degrees of freedom for the swept-wing aircraft during automatic beam approach are shown in Fig. 3. It will be recalled that all the known terms of an equation of motion in each degree of freedom can be represented by a closed chain of time vectors, the angular orientation representing the phase of the maximum of the corresponding term during a full period of the oscillation, and the length of each vector representing its numerical magnitude with respect to the other terms[2]. It is shown in the rolling-moment polygon (Fig. 4 top diagram), that in the present case the aileron-control terms, *viz.*, aileron moment due to heading error, $L_\xi F_\psi \psi$, and aileron moment due to bank error, $L_\xi F_\phi \phi$, are, with the proposed setting of autopilot strengths F_ψ and F_ϕ, numerically much greater than the aerodynamic and inertia terms. In particular, the heading-error term is much larger and is in nearly opposite phase to the rolling moment due to sideslip, $L_\beta \beta$ ($\equiv L_v v/V$). In consequence the resultant excitation of the rolling mode is essentially the difference of the two terms, the dotted line in the polygon. It is in this case larger than the aerodynamic $L_\beta \beta$ by itself and is in opposite phase to it. Therefore the rolling mode is, in spite of an additional large aileron proportional to bank term, still appreciable and in such a phase as to undamp the whole oscillation. The remaining damping, indicated by the magnitude of the apex angle of the shaded isosceles triangle, is very small indeed, in spite of a large autostabiliser term on the rudder, $N_\zeta \zeta$, which in this case trebles the aerodynamic yaw damping, $N_{\dot{\psi}} \dot{\psi}$.

One of the main reasons for this partial cancellation of the yaw damping is the phase lag of the large restoring moment, $N_\beta \beta$, with respect to the kinematic deflection in yaw, ψ, as indicated by the phase angle between $N_\beta \beta$ and the upper (dotted) side of the shaded triangle. This phase angle is created by the cross-wind forces shown in the polygon on the left. The sideways component of the large lift force due to bank, $L_e \phi$, cancels the beneficial $Y_\beta \beta$ term and causes β to lag by an appreciable phase angle against ψ (this angle is the same as the phase lag of $N_\beta \beta$ mentioned above). The severity of this effect of the lift component is due to its magnitude (due to high C_L and particularly the large bank angle ϕ) and its phasing. In both respects it is caused by the automatic aileron steering.

It must be expected that other aircraft also will suffer from this effect to a varying degree. Their main difference with respect to this problem lies in their rolling moment due to sideslip. Therefore an additional set of vector diagrams has been calculated (Fig. 5) for twice the previous L_β. So that the effect can be observed of this variable only, all the other derivatives and control-term strengths of the example in Fig. 4 have been left unchanged.

It can be seen that the excitation of the rolling mode, indicated by the dotted line in the top diagram and essentially determined by the difference of the two opposing rolling moments $L_\beta\beta$ and $L_\xi F_\psi\psi$, is nearly halved. This explains the apparent paradox mentioned before, that increased dihedral reduces the roll/yaw ratio. It is also obvious that this effect changes its sign once the aileron steering term has become numerically smaller than the aerodynamic $L_\beta\beta$.

The smaller bank angle reduces the cross-wind component of the lift force in the equilibrium of cross-wind forces (left-hand diagram). Thus, some small favourable $Y_\beta\beta$ effect remains, giving $N_\beta\beta$ in the yawing-moment diagram, lower right, a small phase lead rather than the large phase lag of the previous case. Consequently the apex angle of the shaded isosceles triangle is reasonably large, *i.e.*, the total damping of the oscillation is good.

A similar effect on the overall damping would of course be experienced with a reduction of the aileron-steering term instead of an increase in the aerodynamic rolling moment due to sideslip. This is, however, a remedy of limited scope for the poor Dutch-roll damping because it adversely affects the damping of the long-period motion about the beam centre-line. It appears more promising to change the effectiveness of the aileron-control term for the different frequencies of the two motions by frequency filtering in the autopilot. In addition, the autostabiliser term in the rudder channel could be further strengthened for the approach condition.

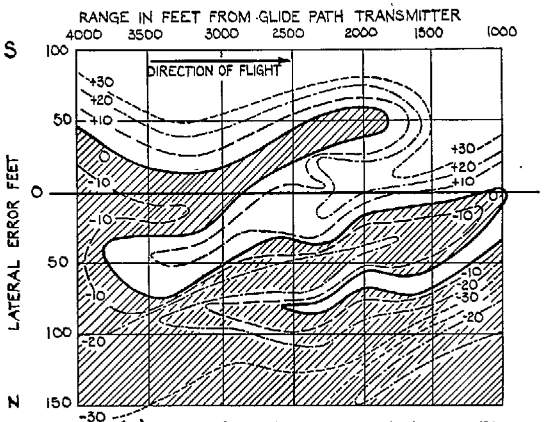
Incidentally, the experience with one straight-wing aircraft brought out a point that should not be overlooked. At first sight the straight, zero-dihedral wing of this aircraft would appear to imply small rolling moments due to sideslip and the aircraft might, therefore, be expected to suffer more from this aileron-steering trouble if the argument developed above is applied. In fact, however, in this case the effective rolling moment referred to inertia in roll is still larger than that of the swept-wing aircraft considered in Fig. 4, so that the case of Fig. 5 is more nearly approached.

LIST OF SYMBOLS

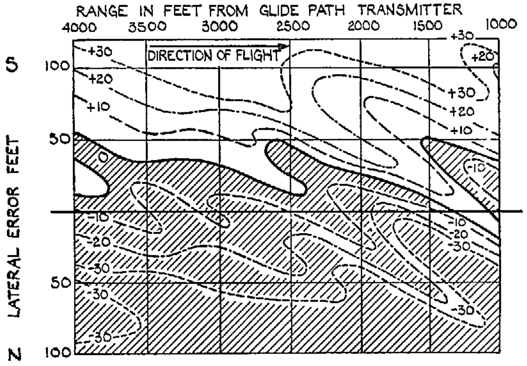
A	Inertia in roll
C	Inertia in yaw
F_ψ	Autopilot gearing, degree control deflection per degree of heading error
F_ϕ	Autopilot gearing, degree control deflection per degree of bank error
K_3	Autopilot setting, relating to F_ψ
L_e	Equilibrium lift force
L_β	Rolling moment due to sideslip
$L_{\dot\psi}$	Rolling moment due to rate of yaw
$L_{\dot\phi}$	Rolling moment due to rate of roll
L_ξ	Aileron effectiveness
N_β	Yawing moment due to sideslip
$N_{\dot\psi}$	Yawing moment due to rate of yaw
$N_{\dot\phi}$	Yawing moment due to rate of roll
N_ξ	Yawing moment due to aileron deflection
N_ζ	Rudder effectiveness
V	Flight speed
Y_β	Cross-wind force due to sideslip
$\dot y$	Rate of deviation from beam centre line
β	$= -\frac{v}{V}$ (Sideslip angle)
ψ	Heading error
χ	Flight-path azimuth error
ϕ	Bank error
ϕ_D	Demanded bank angle
ξ	Aileron angle
ζ	Rudder angle

LIST OF REFERENCES

No.	*Author*	*Title, etc.*
1	E. Downham	The effect of automatic control with aileron steering on the lateral stability and response of a large aircraft. A.R.C. 20,158. November, 1957.
2	K. H. Doetsch	The time-vector method for stability investigations. R. & M. 2945. August, 1953.

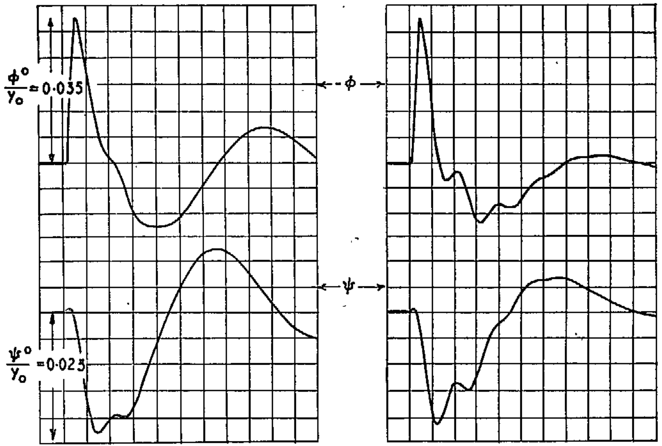


(a) OMNI-DIRECTIONAL I.L.S. AERIAL SYSTEM.



(b) NARROW BEAM I.L.S. AERIAL SYSTEM.

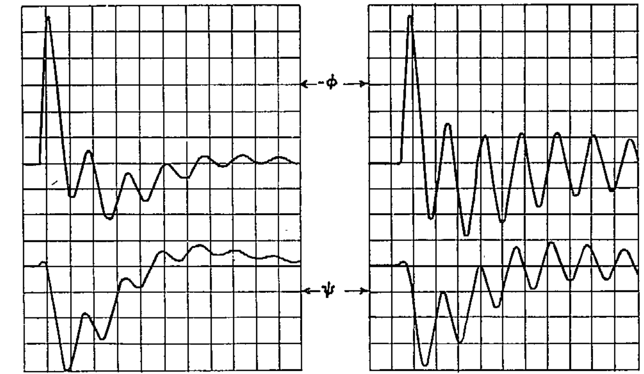
FIGS. 1a and 1b.
Localiser signal pattern.—Woodbridge.



(a) $K_3 = 0{\cdot}25$
Oscillation period = 5·8 secs.

(b) $K_3 = 0{\cdot}5$
Oscillation period = 9·8 secs.

Vertical scale 1" = 0·025° per ft of y_0
Time scale: = 1" = 24 sec.



(c) $K_3 = 0{\cdot}75$
Oscillation period = 9·8 secs.
Damping ratio = 0·05

(d) $K_3 = 1{\cdot}0$
Oscillation period = 9·8 secs.
Damping ratio = 0·04

Approach case:-

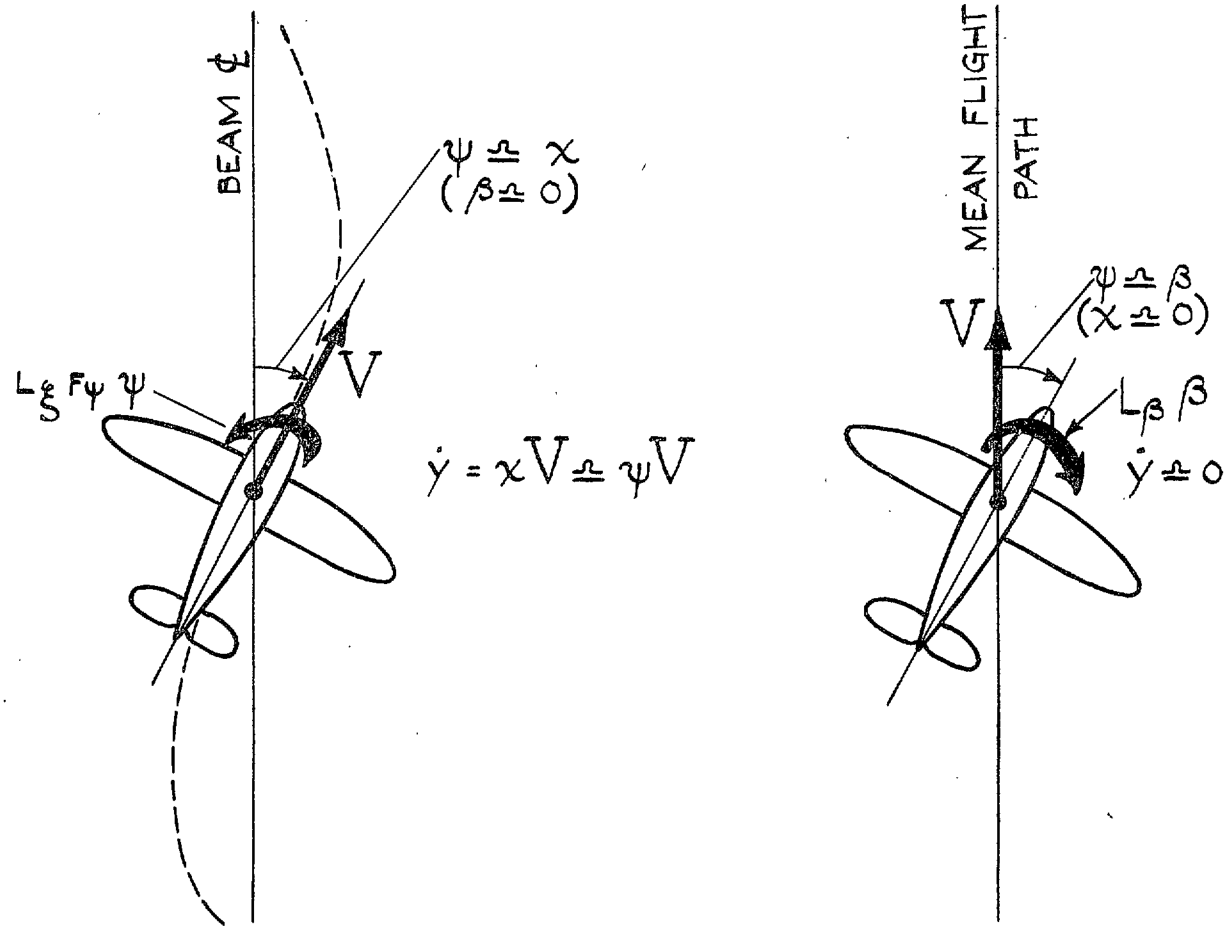
Aileron control:- $\dot{\xi} = F\left[\left(\dot{\phi} - \dot{\phi}_D\right) + C\left(\dot{\psi} - K\phi_D\right)\right]$

Rudder control:- $\dot{\zeta} = H_1\left[\ddot{\psi} - K\dot{\phi}_D\right] - H_2 P$

$$\phi_D = -\frac{K_1}{P}\dot{y} - K_3\dot{\psi}$$

$F = 1$, $C = 1$, $H_1 = 1°$ per °/sec, $H_2 = 0{\cdot}08$ °/sec /° of pendulum angle, $K_1 = 4{\cdot}5$,
$\rho = 2$ miles, Wt = 110000 lb. V = 123 Knts

FIGS. 2a to 2d. The effect of the heading signal gearing K_3.



(a) LONG PERIOD FLIGHT PATH OSCILLATION.

(b) SHORT PERIOD DUTCH ROLL.

FIGS. 3a and 3b. Aircraft heading error.

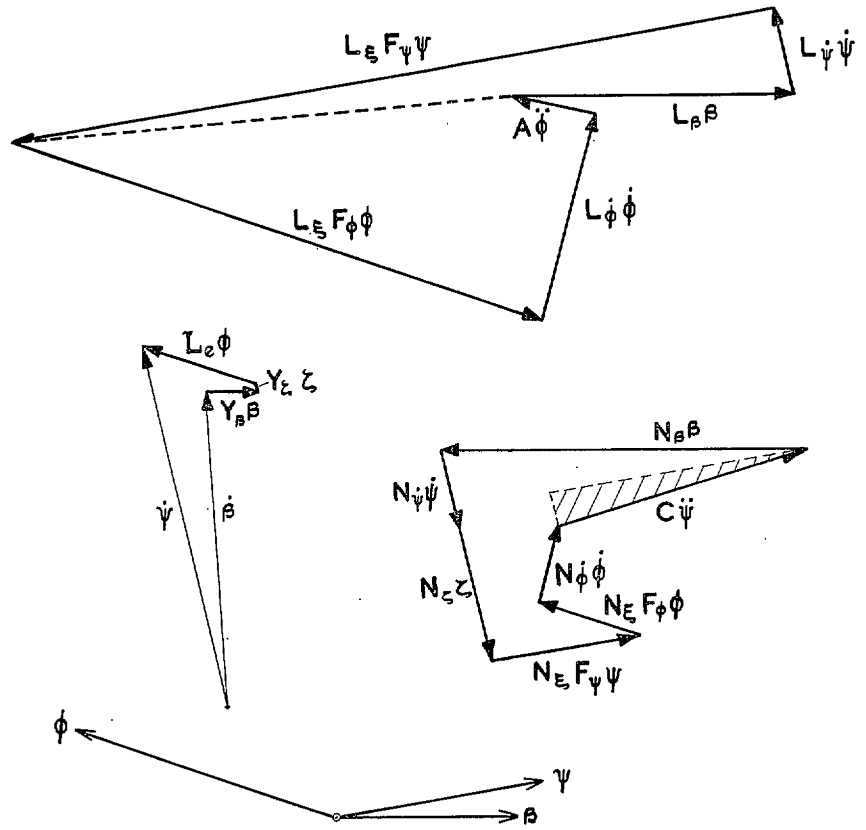


FIG. 4. Aileron steering; approach condition.

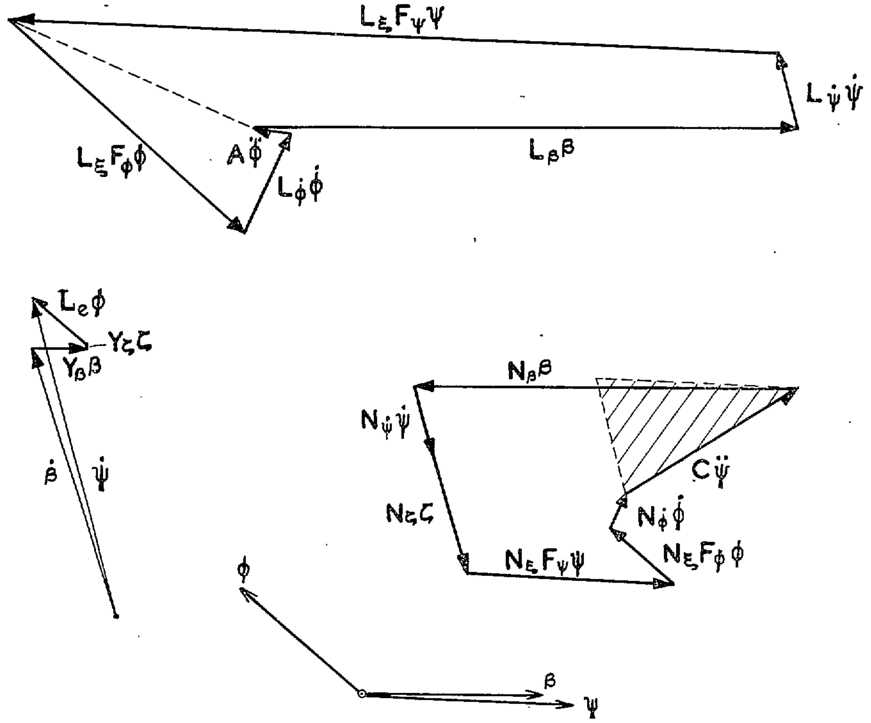


FIG. 5. Aileron steering; large L_β.

(78821) Wt. 54/8210 K.5 11/60 Hw.

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