NINTH EUROPEAN ROTORCRAFT FORUM

Paper No. 70

LATERAL–DIRECTIONAL STABILITY: THEORETICAL ANALYSIS AND FLIGHT TEST EXPERIENCE

A. FAULKNER

Messerschmitt-Bölkow-Blohm GmbH
Munich, Germany

and

M. KLOSTER

Fachhochschule
Munich, Germany

September 13–15, 1983
STRESA, ITALY

Associazione Industrie Aerospaziali

Associazione Italiana di Aeronautica ed Astronautica

LATERAL-DIRECTIONAL STABILITY: THEORETICAL ANALYSIS AND FLIGHT TEST EXPERIENCE

A. Faulkner

Messerschmitt-Bölkow-Blohm GmbH
Munich, Germany
and

M. Kloster

Fachhochschule
Munich, Germany

Abstract

The coupled lateral-directional dynamic stability (Dutch roll) for the helicopter is analysed theoretically using the technique of linearised stability derivatives. Sensitivity studies are used to highlight the most important derivatives for this mode and the model reduction to approximate formulae for the frequency and damping ratio is validated. Data based on parameter identification and a theoretical model are used. The composition of the derivatives is discussed, showing the most important moment and force sources from the rotor, fin and tail rotor. Practical experience from the BK 117 and BO 105 family of helicopters is presented and interpreted. It is shown that nonlinear aerodynamic effects caused by the fuselage and rotor wakes play an important role in the dynamic response and must be considered during the design stage. A balanced tail configuration is suggested.

Notation

I_{xx}, I_{zz}, I_{xz}	[kgm²]	roll, yaw, product moments of inertia
$L_{()}$, $N_{()}$	[Nm]	roll, yaw moment derivatives
$l_{()}$, $n_{()}$		roll, yaw stability derivatives (normalised by inertia)
p, q, r	[°/s]	roll, pitch, yaw angular rates
U_o	[m/s]	trimmed forward velocity
u, v, w	[m/s]	x, y, z velocity perturbations
$y_{()}$	[N]	side force derivative
x, y, z	[m]	body axis system; positive fwd., right, down
Θ, Φ	[°]	pitch, roll attitude
β	[°]	side-slip angle
ω_o	[rad/s]	Dutch roll frequency
ζ		Dutch roll mode relative damping

1. Introduction

With the realisation of the modern high performance helicopter, ever increasing demands have been placed on the aerodynamic aspects to ensure designs compatible with current expectations and specifications. Unlike fixed wing aircraft, the tail rotor and tail surfaces, which provide much of the inherent stability, are forced to operate in less than ideal aerodynamic environments owing to the rotor / fuselage / tail interferences (1). Experience has shown that these influences can be taken into account by modification to conventional aerodynamic theory.

While much recent literature exists with regard to the pure longitudinal flight characteristics, and in the phugoid mode in particular, fewer papers (2) (3) (4) have touched on the lateral and directional motion.

Classical flight mechanics analysis separates the static stability, the control trim positions as a function of flight state, from the dynamic stability which is normally investigated by a linearised small perturbation derivative model. Assuming the helicopter to behave as a rigid body, its motion and dynamic stability in flight can be described by 3 translational plus 3 rotational equations of motion which, when combined with the kinematic relationships, can be written in the familiar matrix form with 8 state variables. Under certain circumstances, where the coupling derivatives are small, it is possible to divide the model into two equation subsets thus separating the longitudinal equations of motion from the lateral-directional.

This model reduction, though clearly inappropriate in hover and low speed flight, is normally permissible for all cruise conditions, as will be demonstrated later.

The lateral-directional stability is characterised by three modes.

- The short roll damping mode is the time constant which dictates the roll rate response following a lateral cyclic control input and is of primary importance in the manoeuvre qualities of the helicopter as discussed in various papers (eg. (5)).
- The slow spiral mode which is of more interest when considering IFR handling qualities.
- The so called "Dutch roll" which is a damped periodic mode, combining roll, yaw and side-slip motion.

It is the Dutch roll mode which is the theme for this paper since its frequency (typical period of oscillation 2 to 5 s) and motion directly affect the flying comfort and pilot workload.

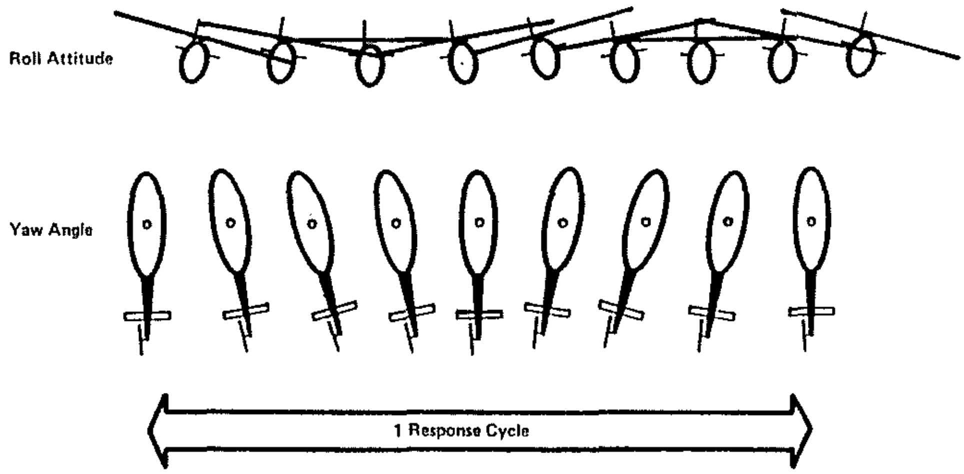

Figure 1 Typical Dutch Roll Mode

Figure 1 shows a typical, for this illustration weakly damped, Dutch roll cycle as viewed from the rear and from above. As the right roll angle recedes, the helicopter yaws nose left, passing though a maximum left yaw shortly before "wings-level". The helicopter continues to roll further left, the nose returning right, and returns to "wings-level" reverting to right roll and left yaw again. Superimposed on the roll-yaw is a lateral motion, not shown in the diagram, and there may be some pitching action.

A poorly damped Dutch roll is to be avoided since the mode will be repeatedly excited by lateral gusts and requires continual pilot corrective action to avoid unpleasant ride qualities.

2. Structure of the Dutch Roll Mode

As stated in the introduction, the classic approach to evaluate the dynamic stability, including the Dutch roll mode, is to analyse the 6 degree-of-freedom linearised derivative model and, in many cases, higher order models including blade dynamics are often recommended. Even a limited 6 d.o.f. model provides little insight, however, into the principal factors of one particular mode and further simplification is essential, provided of course it is physically justified. Though common practice for fixed wing aircraft, it is not immediately obvious that a separation of the longitudinal and lateral-directional stability derivatives for helicopters is permissible. The main rotor itself provides a potential source of coupling which may invalidate the separation concept. Ref. (2), for example, reports on observing significant coupling between the longitudinal and lateral modes during flight tests which influenced the Dutch roll damping. This was attributed to rotor torque variation resulting from the vertical motion of the helicopter. For these reasons, a systematic model reduction and comparison are necessary.

To avoid erroneous conclusions owing to possible incorrect assumptions and modelling errors involved in a purely theoretical derivative model, the following analysis is based on a hybrid of identified derivatives and theoretical values.

Theoretical Derivatives - The theoretical derivatives have been obtained from a fully nonlinear rotorcraft stability analysis program (STAN). In addition to the basic fuselage 6 d.o.f., the program includes optional higher order rotor dynamics such as flapping, lagging and torsional modes. Tabulated wind tunnel data for the blade profiles, fuselage and aerodynamic surfaces as well as interference effects between rotor / fuselage and rotor / empennage are included. For the purpose of this study, the higher order blade modes were neglected since analysis showed them to have negligable influence on the slower Dutch roll.

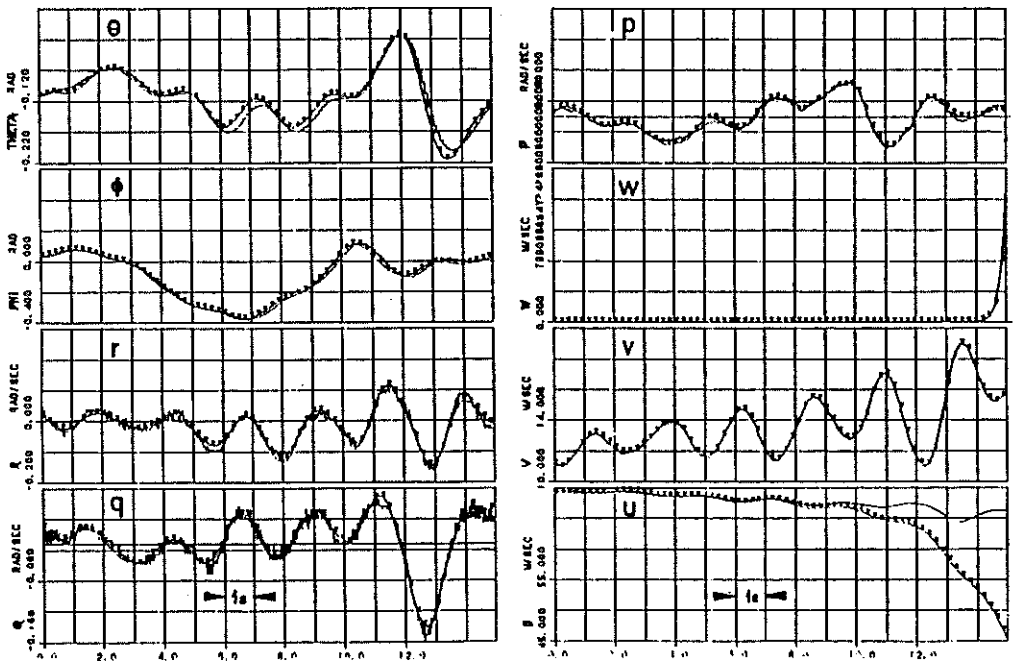

Figure 2 BO 105: Time History Comparison during Parameter Identification at 120 kTAS

System Identification - In a joint programme between MBB and the DFVLR, flight tests were performed to identify the stability derivatives of the BO 105 at various flight states. A summary of the principal results and findings is given in (6). Included in the tests were a number of runs with optimised lateral control inputs designed to excite the lateral-directional modes. From this data, it was possible to identify with confidence a significant number of derivatives for which the time history response compared well with flight tests (Figure 2).

Reduced Systems - The complete coupled longitudinal / lateral stability matrix resulting from a combination of theoretical and identified derivatives for a typical 120 KTAS cruise condition with the BO 105 is given in Table 1. The origin of each derivative is indicated.

BO 105 SYSTEM-MATRIX

	u	w	q	v	p	r
x	-3.700000D-02 ●	-4.000000D-02 o	8.000000D-02 o	9.000000D-02 ●	-1.800000D-01 o	0.000000D-01 o
z	4.000000D-02 o	-6.000000D-01 ●	1.100000D 00 o	-1.000000D-02 o	0.000000D-01 o	0.000000D-01 o
m	1.146000D 00 ●	2.292000D 00 ●	-3.700000D 00 ●	2.000000D-02 ●	-5.000000D-01 ●	-8.000000D-01 ●
y	0.000000D-01 o	0.000000D-01 o	1.700000D-01 ●	-2.600000D-01 ●	-1.000000D-01 o	-1.100000D 00 ●
l	-1.719000D 01 ●	-4.011000D 00 ●	4.500000D 00 ●	-2.120000D 01 ●	-7.650000D 00 ●	-1.890000D 00 ●
n	-1.719000D 00 ●	-2.272000D 00 ●	2.000000D 00 ●	1.719000D 00 ●	-2.390000D 00 ●	-2.170000D 00 ●

● Derivatives estimated from system-identification (several flight tests avergage values)
o Derivatives estimated with stability analysis program (smoothed values)

EIGENVALUES

FULL SYSTEM (8 * 8)

LONGITUDINAL

-2.4353630D-01	0.0000000D-01
-5.0966767D 00	0.0000000D-01
2.4204406D-01	-3.1773302D-01
2.4204406D-01	3.1773302D-01

LATERAL

-1.7963735D-01	0.0000000D-01
-8.8274410D 00	0.0000000D-01
-2.7689842D-01	-2.5980267D 00
-2.7689842D-01	2.5980267D 00

LATERAL SUBSET (4 * 4)

LATERAL

-1.3012382D-01	0.0000000D-01
-9.3520770D 00	0.0000000D-01
-2.9889958D-01	-2.7263124D 00
-2.9889958D-01	2.7263124D 00

Table 1 BO 105: System–Matrix and Eigenvalues

Comparison of the lateral eigenvalues derived for the complete coupled (8 x 8 matrix) and the lateral subset (4 x 4) shows very good agreement, in particular the Dutch roll mode, thus demonstrating the validity of the system reduction. Furthermore, the eigenvalues of the longitudinal motion, for example the phugoid mode, agreed very well with flight measurement thus adding confidence to the overall derivative set.

A sensitivity analysis on the coupling derivatives also supported the validity of the longitudinal and lateral separation. From the basic derivative set given in Table 1, variation in the coupling derivatives produced little change in Dutch roll frequency or damping ratio as illustrated in Figure 3. The vertical velocity to yaw derivative n_w, which was the major source of coupling reported in (2), had little influence on the Dutch roll mode for the BO 105.

A similar derivative sensitivity analysis for the 4 x 4 lateral subset alone provides a useful indication of the dominant parameters. In the data presented in Figure 4 each derivative has been varied in turn from zero to twice the value of the original given in Table 1.

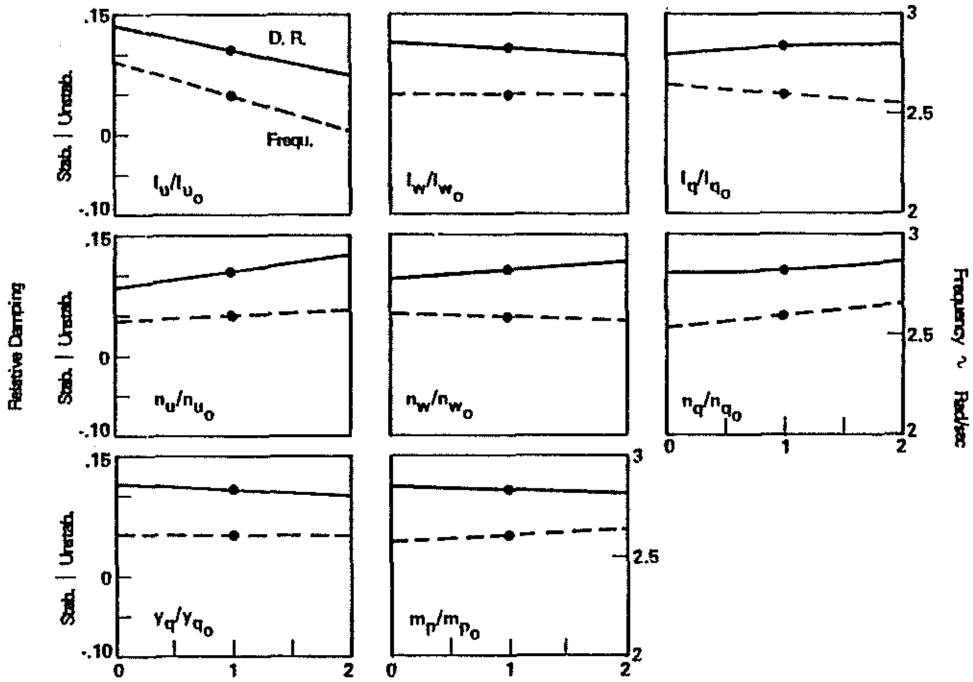

Figure 3 BO 105: Sensitivity Analysis of Coupling Derivatives

It should be noted that not only the direct yaw rate damping derivative n_r but also the roll rate damping l_p and roll / side-slip l_v play a significant part in the Dutch roll damping ratio. In practice, however, it is rarely possible to influence one derivative in isolation, so an aircraft design change will normally involve a complex interplay of derivative variation rather than the idealisation shown in Figure 4.

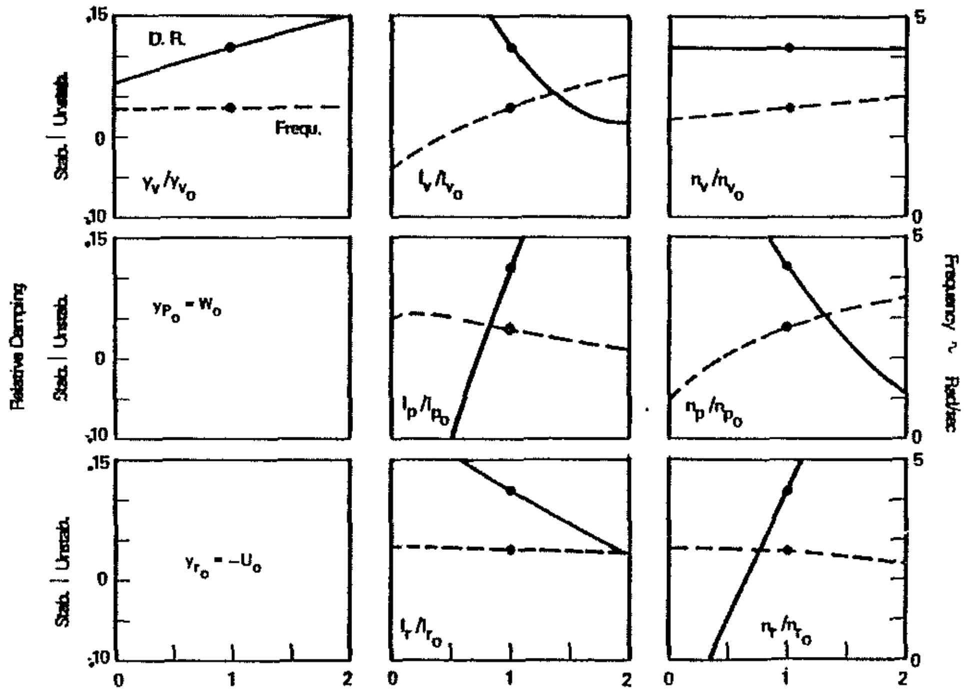

Figure 4 BO 105: Sensitivity Analysis of Lateral Subset

Assuming the translation content of the Dutch roll mode to be minimal and the roll / yaw motion to be dominant, Seckel (7) suggests the following approximation;

$$s^2 + 2\,\zeta\,\omega_o\,s + \omega_o^2 = o$$

with

$$\omega_o \ \text{(frequency)} = \sqrt{U_o\,(n_v - l_v \cdot \frac{n_p}{l_p})}$$

$$\zeta \ \text{(damping ratio)} = \frac{1}{2\,\omega_o}\left[-n_r + l_r\,\frac{n_p}{l_p} - U_o \cdot l_v \cdot \frac{n_p}{l_p^2} \right] \qquad \ldots . \quad (1)$$

This approximation was found to compare well with both the 8 x 8 and 4 x 4 subset solutions discussed above and the values obtained from flight test records (Table 2).

	8 * 8	4 * 4	Seckel approx.	BO 105 LS flt. test
ω_o	2.61	2.75	2.65	2.70
ζ	0.107	0.109	0.109	0.100

Table 2 Dutch Roll Results of MBB–BO 105 Helicopter

Moment Derivatives - For the helicopter design layout or for modification to an existing design, it is necessary to understand the composition of the stability derivatives in terms of the individual moment components. A good theoretical model is essential which can then be proven against flight test results or identified derivatives. Measurement of the individual moment components themselves is of course impossible, however, the same forces (eg. from fin, tail rotor) may appear in several different moment derivatives so that some crosschecking is possible.

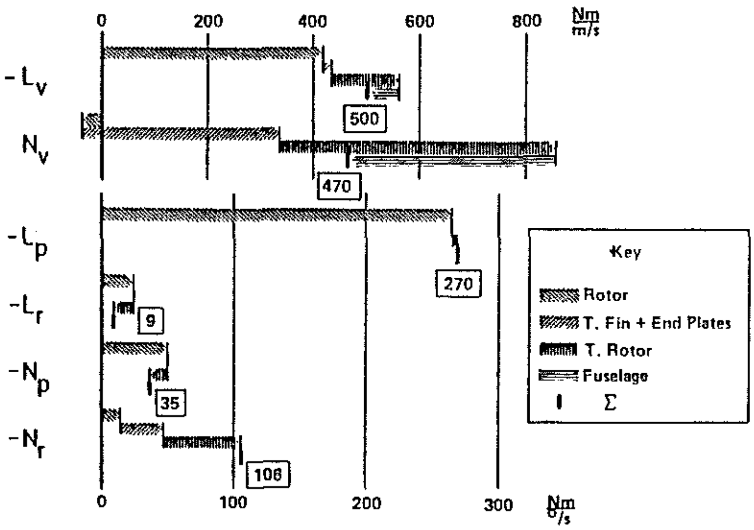

Figure 5 Typical Composition of Lateral Moment Derivatives – Theoretical Basis at 110 kTAS

A typical breakdown of the lateral moment derivatives theoretical basis at 110 KTAS) is given in Figure 5. As i expected with hingeless rotor systems, the roll derivatives L_p, L are dominated by the main rotor. The yaw derivatives N_v, dependent mostly on the fin / vertical aerodynamic surfaces a tail rotor. Both L_r and N_p, the cross-coupling derivatives, are virtually negligible and in fact the principal element in N_p is cause by the transformation of L_p through the 5° forward tilt of the rotor mast into the helicopter body axes. The assembly of the important derivatives is summarized qualitatively below;

$$
\begin{array}{llllll}
L_v & \rightarrow & L_{v\,Rot.} & + \; L_{v\,Fus.} & + \; z \cdot & (Y_{v\,T.Rot.} + Y_{v\,Fin}) \\
N_v & \rightarrow & & N_{v\,Fus.} & + \; x \cdot & (Y_{v\,T.Rot.} + Y_{v\,Fin}) \\
L_p & \rightarrow & L_{p\,Rot.} & & & \\
N_r & \rightarrow & & & x^2 \cdot & (Y_{v\,T.Rot.} + Y_{v\,Fin})
\end{array}
\qquad \ldots\ldots \quad (2)
$$

(NB: The sign of each term is dependent on configuration)

Refering to Equations (1) and (2) it can be seen not only how fin or tail rotor size will alter the Dutch roll frequency and damping ratio, but also increasing the main rotor roll / side-slip L_v characteristic or reducing the main rotor roll damping L_p will have an adverse effect on the damping ratio. However, as is clear from Equations (1), this effect pre-supposes a significant value for n_p which is evident in the stability derivatives in Table 1 but not in the moment derivatives of Figure 5. The anomaly is to be found in the choice of axis system.

<u>Principal Axes of Inertia</u> - The constructional or measurement axes, chosen for convenience, rarely coincide with the principal inertial axes which, owing to the configuration of the tail above and behind the mass centre, rotates the principal inertial axis approximately 15° downward relative to the cabin floor. Neglecting second order terms, the stability derivatives can be approximated by;

$$
l_{(-)} = \frac{1}{I_{xx}} \cdot L_{(-)} + \frac{I_{xz}}{I_{xx}\, I_{zz}} \cdot N_{(-)}
$$

$$
n_{(-)} = \frac{1}{I_{zz}} \cdot N_{(-)} + \frac{I_{xz}}{I_{xx}\, I_{zz}} \cdot L_{(-)} \qquad \ldots\ldots \quad (3)
$$

With a typical value of $I_{xz} : I_{zz} \approx 0.4$ it can be seen for example that L_p becomes significant in n_p.

By combining Equations (3) and (2) and neglecting small terms very approximate expressions can be obtained as;

$$\omega_o = \sqrt{U_o \cdot \frac{N_v}{I_{zz}}}$$

$$\zeta = \frac{1}{2\,\omega_o} \left[\frac{-N_r}{I_{zz}} - U_o \cdot \frac{L_v}{L_p} \cdot \frac{I_{xz}}{I_{zz}} \right] \qquad \ldots\ldots (4)$$

which serve to illustrate how the inertial products can influence the damping ratio.

3. Selected Flight Test Observations and their Interpretation

The following are a collection of flight test measurements from various experimental and development programmes and are used to illustrate some of the effects discussed in the previous section.

Influence of Airspeed - As predicted by the Seckel equations, the Dutch roll frequency increases and the period of oscillation decreases with airspeed as shown in Figure 6.

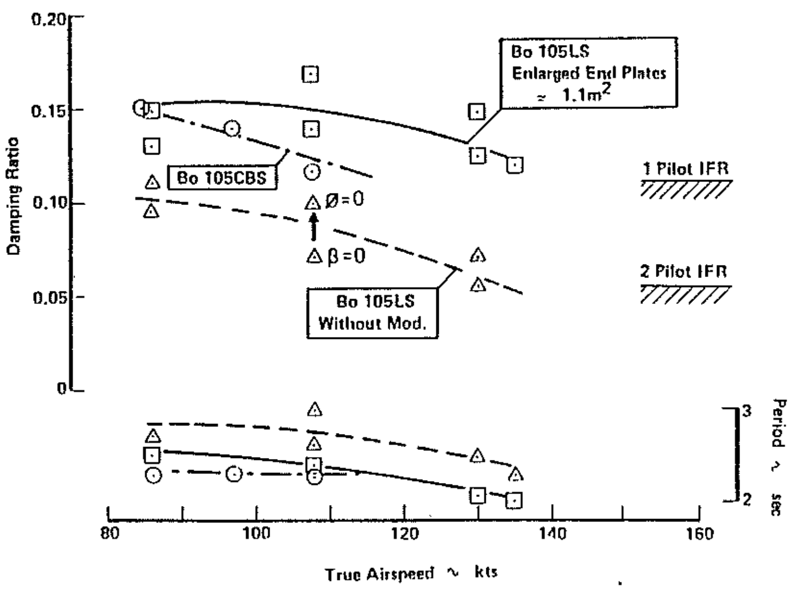

Figure 6 BO 105 CBS/LS: Dutch Roll Damping and Period of Oscillation

The variation is roughly proportional since the n_v derivative itself also increases with airspeed. The contribution to the derivative from the fin and end plates increases linearly whereas, apart from the effects due to the induced velocity variation, the tail rotor contribution remains constant as a function of speed.

Despite the improved yaw damping n_r with airspeed (caused by the same effect as for n_v), the roll / side-slip derivative l_v increasingly works to destabilise the Dutch roll mode and hence the damping ratio tends to fall. However, this usually reaches a minimum before increasing again at higher cruising speeds, as was observed during BK 117 flight testing (5), and is attributable to the complex structure of the wake to be found at the tail.

Aerodynamic Flow at Tail - Rotor downwash, rotor hub and fuselage wakes combine to disturb the air mass impinging on the tail, directing the flow downwards and to the left side of the tail fin. At the same time, there is a dynamic pressure loss which reduces the efficiency of the aerodynamic surfaces. Flight test measurements from several sources (3) (5) indicate that a peak pressure loss of 50 % is common. Furthermore, the position of the pressure loss is dependent on the trimmed flight state as is evident from Figures 7 and 8.

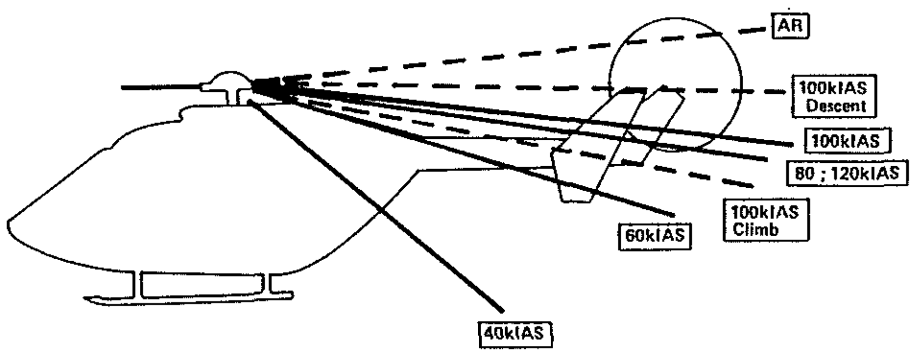

Figure 7 **Typical Aerodynamic Flow Direction (Variation with Flight Condition)**

At lower forward speeds the region of pressure loss passes below the tail. At higher cruise speeds there is the maximum effect on the tail rotor and vertical surfaces, and, as speed is further increased, cleaner air once again returns to the tail. In global terms, an efficiency factor can be included in the theoretical calculations to account for the phenomenon. In the worst case, the factor reaches around 70 % efficiency of the theoretical value for the tail under ideal conditions.

As shown in Figure 8, the flow conditions at the tail are similarly improved as the helicopter starts to descend. Clean air is admitted from below and the efficiency of the fin and end plates increases substantially.

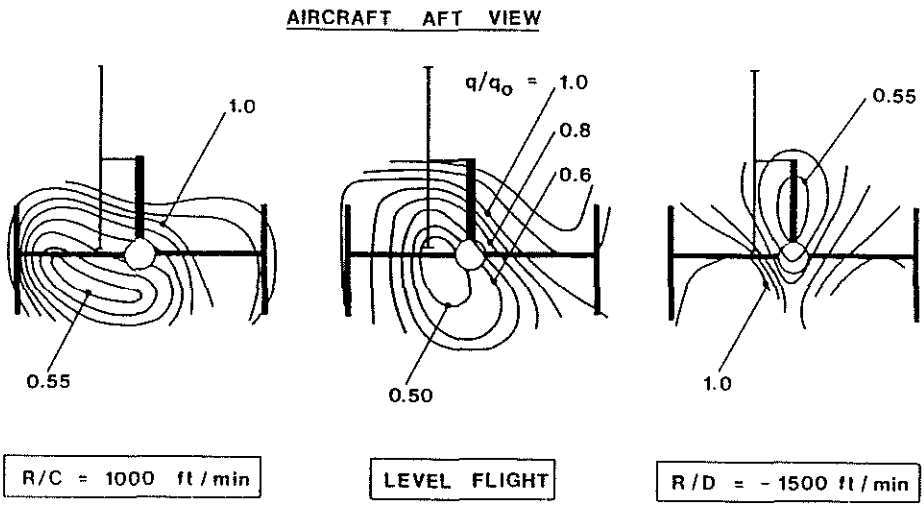

Figure 8 Typical Dynamic Pressure at Tail Area (80 kts IAS)

The problem of dynamic pressure loss is inherent with all tail configurations. A high or low design may have particular advantages at one trimmed flight state but to the detriment of another. The designer's task is to find the best compromise while taking into account other factors such as structural constraints.

Tail Size and Geometry - The primary term in the equation for the damping ratio (1) is of course the direct yaw rate damping n_r. The second two terms in the equation always oppose the effects of n_r thereby reducing the damping ratio as previously discussed. Increasing the size of any of the vertical aerodynamic surfaces (fin, tail rotor area) will improve n_r and consequently the Dutch roll mode, raising the natural frequency and the damping ratio. Another effective method of increasing n_r is to add larger end plates to the tailplane to avoid the region of dynamic pressure loss near the fin. A good aspect ratio is also desirable, which can be achieved by extending the end plate vertically and sweeping back the leading edge at the top to compensate for the downward angle of attack caused by the main rotor wake. It may also be found that, apart from improving the aspect ratio, the vertical form will enjoy less turbulent flow and will operate more efficiently. Both Dutch roll damping ratio and frequency are increased as shown in Figure 6. A typical pedal disturbed response is shown in Figure 9.

Trim and Side-Slip Effects - Most theoretical work is performed under the assumption that the helicopter is trimmed to zero side-slip. However, unlike fixed wing aircraft, this results in a slight roll left attitude (typically 3 or 4°) owing to the asymmetric side force caused by the tail rotor thrust. Many pilots trim out this condition, preferring to fly with a zero roll attitude and nose left side-slip.

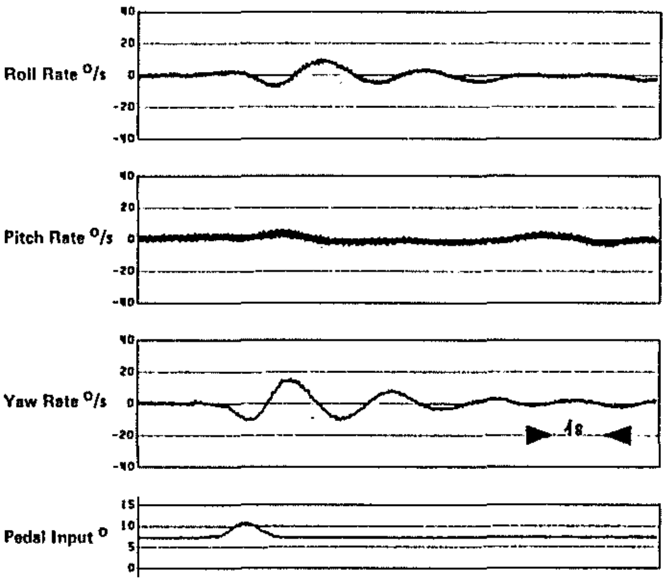

Figure 9 BO 105LS: Dutch Roll Characteristics at 130 kts

The wake core wanders further left as a consequence so that the tail rotor and fin are able to operate in a more stable aerodynamic environment. The effect on the Dutch roll damping and frequency is shown in Figures 6 and 10. Surprisingly, when asked to fly either roll attitude zero or yaw attitude zero, the pilot trimmed with essentially the same control settings. This observation can only be explained by the complex structure of the wake causing nonlinear trim effects. Some of the test scatter can hence be explained by varying piloting techniques resulting in differing trim states.

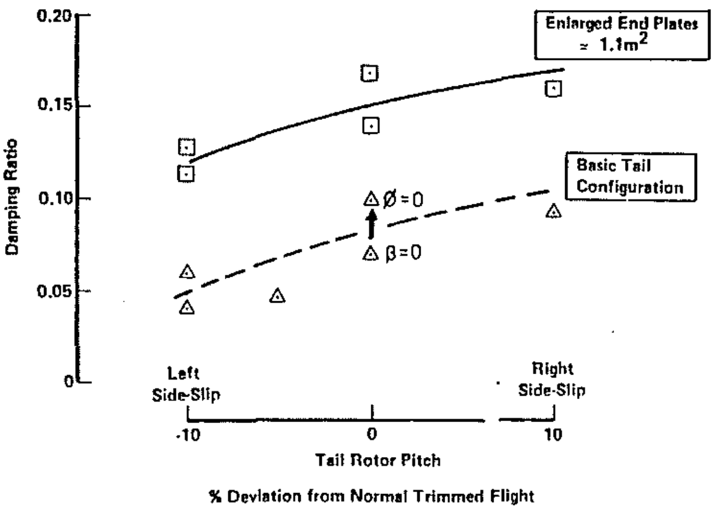

Figure 10 BO 105LS: Influence of Side-Slip on Dutch Roll Damping

Tests with both the BK 117 and BO 105 LS showed that under extreme right side-slip conditions the wake core passed away to the left of the left end plate so that the tail surfaces operate more efficiently with the converse true in left side-slip. Consequently, variation in the damping ratio will be encountered dependent on tail rotor pitch angle as shown in Figure 10 for a typical 110 KTAS horizontal cruise condition. The effect is also evident at other flight states, such as climb, where the wake remains in the general proximity of the tail. This is illustrated in Figures 11 and 12 where a dramatic increase in Dutch roll damping ratio can be seen in right side-slip.

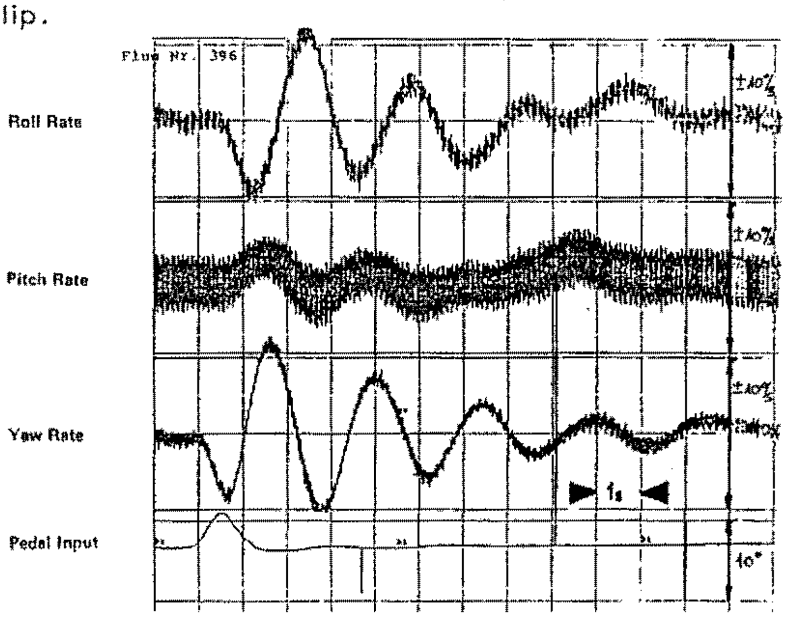

Figure 11 BK 117: Typical Dutch Roll Characteristics at 95 kts MCP Climb (Left Side-Slip)

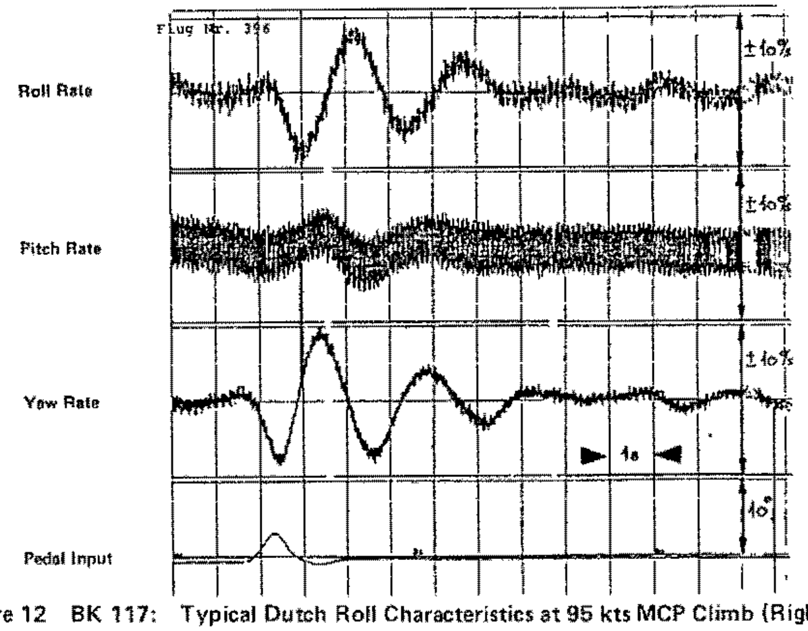

Figure 12 BK 117: Typical Dutch Roll Characteristics at 95 kts MCP Climb (Right Side-Slip)

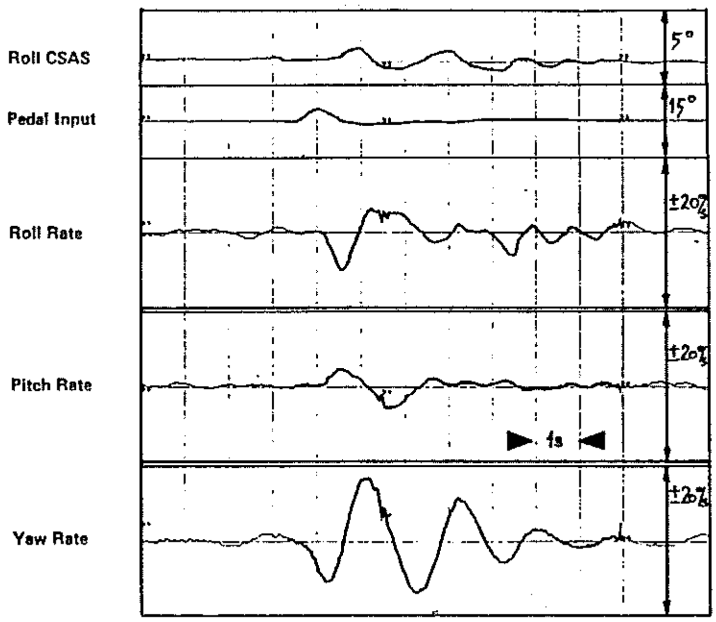

Figure 13 BO 105LS: Dutch Roll Characteristics with CSAS at 130 kts

Effect of Roll Damping - As previously discussed, the roll rate damping l_p will influence the Dutch roll mode. This is most evident by referring once again to Equations (1) where it can be seen that l_p appears in the denominator of the second and third terms, which are destabilising. If it were possible to infinitely increase the roll damping, the destabilising terms would reduce to zero and only a highly damped pure yaw mode would remain.

Referring to Figure 5 once again, it will be seen that l_p is entirely dependent on the main rotor characteristics and specifically the blade Lock's number. Reducing the Lock's number, by minimising blade area or increasing blade mass will improve the roll damping. However, major changes to the rotor system are not possible to impliment for experimental purposes. Neither is the designer free to choose the Lock's number at will. From a flight mechanics point of view small area, high mass blades are advantageous. For blade dynamic stability, aerodynamic efficiency and to reduce structural loads and helicopter weight, the opposite is true.

The roll damping can, however, be improved or a rotor design variation simulated by the inclusion of a simple control and stability augmentation system (CSAS). Figure 13 shows a typical pedal input response with the CSAS engaged. As theoretically predicted, the rolling motion is reduced and the damping of the remaining periodic yaw response substantially increased.

A Balanced Design - It can be seen from the previous discussion that the designer has several possibilties to ensure good Dutch roll characteristics. The primary consideration must be to ensure an adequate value of the direct yaw damping derivative n_r. However, within limits, this can be achieved by different combinations of tail rotor and fin sizes. The distribution of the equivalent area over a tail rotor / fin / end plate combination is particularly attractive.

A physical separation of fin and end plates helps to reduce the unavoidable problem of the wake and dynamic pressure loss. Even in the most unfavourable flight condition, sufficient vertical aerodynamic surface will be in the undisturbed free stream.

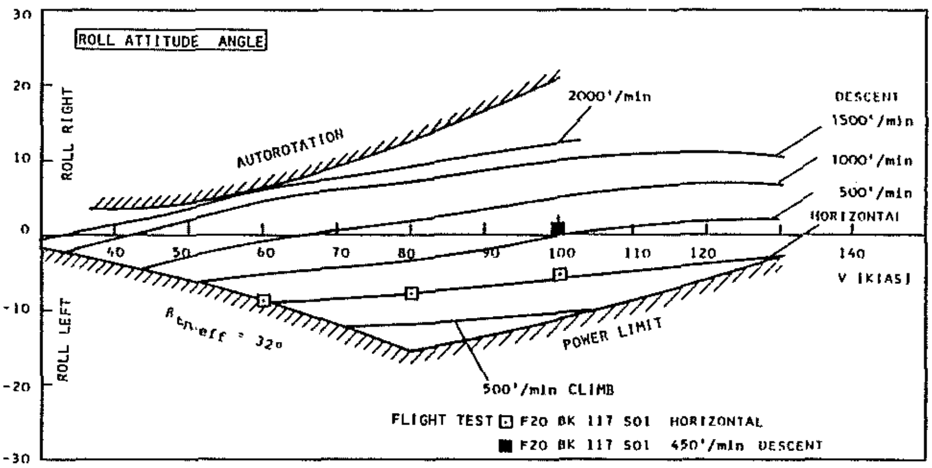

Figure 14 BK 117: Possible Flight Envelope Following Tail Rotor Loss (Roll Attitude)

The distribution between passive area (fin + end plates) and active area (tail rotor) has the advantage of relieving the tail rotor during normal high speed cruise flight. Furthermore, though not a requirement for civil helicopters, there is the added safety advantage in the event of complete tail rotor loss. Theoretical analysis and flight simulation with the BK 117 demonstrated that a wide horizontal speed range from about 60 kts to V_H is still possible without excessive left roll or side-slip (Figures 14 and 15).

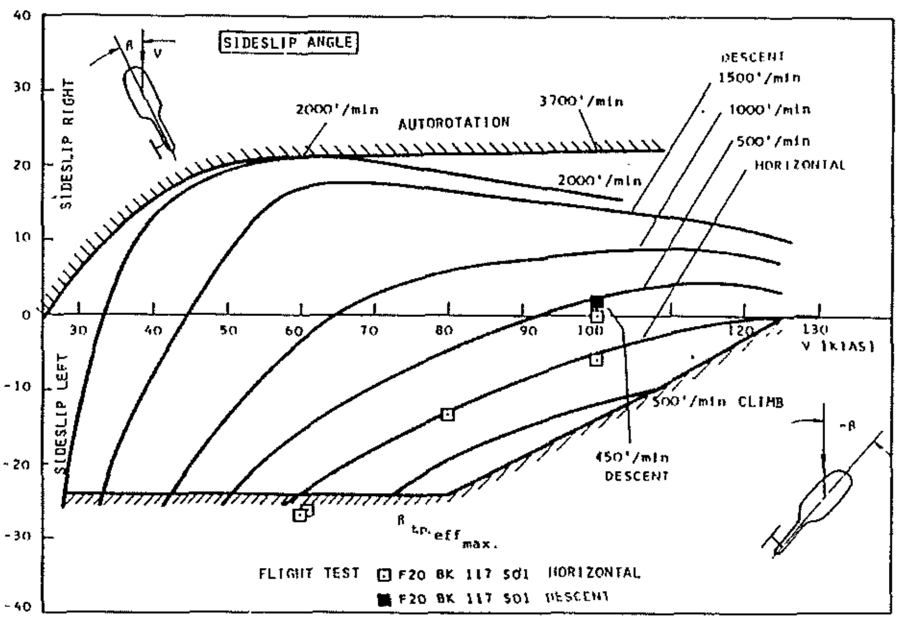

Figure 15 BK 117: Possible Flight Envelope Following Tail Rotor Loss (Side-Slip Angle)

At minimum power speed of about 70 kts climb rates in excess of 500 ft/min can be achieved with maximum take-off weight. Below 60 kts a partial powered descent ensures that the side-slip angle remains acceptable. Finally, an emergency power-off landing can be executed at an acceptable forward speed.

4. Concluding Remarks

- It has been demonstrated with the aid of identified stability derivatives that reduced order models can give a good approximation to the Dutch roll mode of helicopters with hingeless rotor systems.

- The unsteady aerodynamic conditions at the tail must be considered in the flight mechanics model.

- A balanced design between tail rotor and vertical aerodynamic surfaces offers an additional safety factor in the event of tail rotor failure.

5. References

(1) H. Huber, G. Polz: Studies on Blade-to-Blade and Rotor-Fuselage-Tail Interferences.

Presented at the AGARD Fluid Dynamics Panel Specialists' Meeting on "Prediction of Aerodynamic Loads on Rotorcraft", London, May 17-18, 1982.

(2) G.D. Padfield, R.W. DuVal: Applications of System Identification Methods to the Prediction of Helicopter Stability, Control and Handling Characteristics.

Presented at the Specialists Meeting on "Helicopter Handling Qualities", Ames Research Center, Moffett Field, California, April 14-15, 1982.

(3) P. Roesch, A. Vuillet: New Designs for Improved Aerodynamic Stability on Recent Aerospatiale Helicopters.

Presented at the 37th Annual Forum of the American Helicopter Society, New Orleans, Louisiana, May, 1981

(4) R.W. Prouty: Practical Helicopter Aerodynamics. PJS Publications Inc., 1982

(5) H. Huber, T. Masue: Flight Characteristics Design and Development of the MBB/KHI BK 117 Helicopter.

Presented at the 7th European Rotorcraft and Powered Lift Aircraft Forum, Garmisch-Partenkirchen, Germany, Sept. 8-11, 1981

(6) M. Kloster, J. Kaletka, H. Schäufele: Parameter Identification of a Hingeless Rotor Helicopter in Flight Conditions with Increased Instability.

Presented at the 6th European Rotorcraft and Powered Lift Aircraft Forum, Bristol, England, Sept. 16-19, 1980

(7) E. Seckel: Stability and Control of Airplanes and Helicopters. Academic Press, 1964