WHY BIRDS AND AIRPLANES NEED NO VERTICAL TAIL

Abstract

The question of why airplanes need a vertical tail whereas birds seem to do very well without one has been longstanding. Some have suggested that it is a matter of scale; that the rationale for a vertical tail disappears when coming down the scale from the regime of "full" scale aircraft to bird/ small scale flight regime. This hypothesis has now been debunked. This paper shows that the lateral-directional modal dynamics and stability criteria remain unchanged over the relevant range of flight Reynolds numbers. It conclusively establishes that a vertical tail is not essential for directional or lateral stability at any scale from that of bird flight to "full" scale airplane flight.

Introduction

It has intrigued aeronautical scientists and engineers forever that the most adept flyers, the avians, have no need for a vertical tail. In contrast, almost every airplane designed over the last century of flight, but for a very small number of "tailless" ones, [1] sports a vertical tail; some have two, an odd one even has three. Ventral and dorsal fins to augment the vertical tail are commonly observed. The purpose of the vertical tail in its various forms is commonly explained as providing directional stability and damping in yaw. Additionally, the deflectable rudder surface at the trailing edge of the vertical tail is meant to provide directional control. This leads one to the obvious question: How do birds manage directional stability and control sans a vertical tail? Or is it that birds fly with some degree of lateral-directional instability, as some [2] have suggested?

One point of view [3] is that it is a matter of scale; that the rationale for having a vertical tail disappears at the smaller scale corresponding to the flight of birds and "mini" scale airplanes. The implication being that "full" scale airplanes would generally continue to require a vertical tail to satisfy lateral-directional flight requirements. Yet, we have examples (see Fig.1) of airplanes designed with a vertical tail that have managed to fly safely despite almost all of the vertical tail being accidentally lost. Hang gliders are another example of a system that does very well without the need for a vertical tail [16].

The basis for most conclusions regarding the need or otherwise of a vertical tail for flight stems from an analysis of the literal approximation to the lateral-directional modes, particularly the dutch roll and spiral modes. However, as the present authors have shown in recent papers [4,5] and in their textbook [6], the traditional approximations to the dutch roll and spiral modes are erroneous. There are three main sources of error. The first being the incorrect definition and usage of the dynamic (rate) derivatives, traditionally labeled $C_{mq}$, $C_{nr}$, $C_{lp}$, etc., in the aerodynamic model used with flight dynamics, an unfortunate legacy from the early work by Bryan [7]. The second one is because the timescales associated with the various modes have traditionally never been clearly defined and used as the basis for analytically separating the modes from one another. And thirdly, the static residual of the faster mode dynamics has not been used when deriving the approximation to the slower mode. These errors and the consequences thereof have been highlighted by the authors in several publications [8,9,10,11]. As a result, it has become necessary to review and re-examine the conclusions regarding the relation between directional
stability and the presence of the vertical tail in the light of
the corrected literal approximations to the lateral-directional modes [5].

In this paper, we shall show how stability of the dutch roll and spiral modes can be obtained in principle for any airplane without the need for a vertical tail.

**Corrected Lateral-Directional Dynamics**

Under the usual assumptions of small perturbations in the lateral-directional variables alone, about a straight and level flight trim state, the lateral-directional equations of motion may be written as [5]:

$$\Delta \dot{\chi} = \left(\frac{g}{V^*}\right) \left[ \left(\frac{q S}{W}\right) \Delta C_Y + \Delta \mu \right]$$

(1)

$$\Delta \dot{\mu} = \left(\frac{q S b}{I_{xx}}\right) \Delta C_I = \left(\frac{I_{zz}}{I_{xx}}\right) \left(\frac{q S b}{I_{zz}}\right) \Delta C_I$$

(2)

$$\Delta \dot{\psi} = \left(\frac{q S b}{I_{zz}}\right) \Delta C_n$$

(3)

where $\Delta \chi$ is the perturbed wind-axis (velocity vector) yaw angle, $\Delta \mu$ is the wind-axis roll angle, and $\Delta \psi$ is the body-axis yaw angle, $q$ is the dynamic pressure ($= \frac{1}{2} \rho V^2$), $S$ is a reference area, usually the airplane wing planform area, $b$ is the wing span, $g$ is the acceleration due to gravity, $W$ is the airplane weight, $I_{xx}, I_{zz}$ are the moments of inertia, $V^*$ is the trim velocity, and the perturbed aerodynamic coefficients are modeled as:

$$\Delta C_Y = \frac{\partial C_Y}{\partial \beta} \Delta \beta + C_{\beta 1} \left(\frac{\partial \beta}{\partial \beta} - \Delta \beta \right) \left(\frac{h}{2/2} \right)^* + C_{\beta 2} \Delta p_w \left(\frac{h}{2/2} \right)^* + C_{\beta 3} \Delta r_w \left(\frac{h}{2/2} \right)^* + C_{\beta 4} \left(\frac{\partial \beta}{\partial r} - \Delta \beta \right) \left(\frac{h}{2/2} \right)^* + C_{\beta 5} \Delta r_w \left(\frac{h}{2/2} \right)^* + C_{\beta 6} \Delta r_w \left(\frac{h}{2/2} \right)^*$$

(4)

$$\Delta C_I = \frac{\partial C_I}{\partial \beta} \Delta \beta + C_{\beta 1} \left(\frac{\partial \beta}{\partial \beta} - \Delta \beta \right) \left(\frac{h}{2/2} \right)^* + C_{\beta 2} \Delta p_w \left(\frac{h}{2/2} \right)^* + C_{\beta 3} \Delta r_w \left(\frac{h}{2/2} \right)^* + C_{\beta 4} \left(\frac{\partial \beta}{\partial r} - \Delta \beta \right) \left(\frac{h}{2/2} \right)^* + C_{\beta 5} \Delta r_w \left(\frac{h}{2/2} \right)^* + C_{\beta 6} \Delta r_w \left(\frac{h}{2/2} \right)^*$$

(5)

$$\Delta C_n = \frac{\partial C_n}{\partial \beta} \Delta \beta + C_{\beta 1} \left(\frac{\partial \beta}{\partial \beta} - \Delta \beta \right) \left(\frac{h}{2/2} \right)^* + C_{\beta 2} \Delta p_w \left(\frac{h}{2/2} \right)^* + C_{\beta 3} \Delta r_w \left(\frac{h}{2/2} \right)^* + C_{\beta 4} \left(\frac{\partial \beta}{\partial r} - \Delta \beta \right) \left(\frac{h}{2/2} \right)^* + C_{\beta 5} \Delta r_w \left(\frac{h}{2/2} \right)^* + C_{\beta 6} \Delta r_w \left(\frac{h}{2/2} \right)^*$$

(6)

where $\beta$ is the sideslip angle, $p, r$ are the roll and yaw rates respectively, the subscripts ‘$b$’ and ‘$w$’ refer to body-axis and wind-axis quantities respectively, and the various aerodynamic derivatives are defined as below:

$$C_{\beta \beta} = \frac{\partial C_Y}{\partial \beta \beta}$$

$$C_{\beta p} = \frac{\partial C_Y}{\partial \beta p}$$

$$C_{\beta w} = \frac{\partial C_Y}{\partial \beta w}$$

$$C_{p p} = \frac{\partial C_Y}{\partial p p}$$

$$C_{w w} = \frac{\partial C_Y}{\partial w w}$$

$$C_{w w} = \frac{\partial C_Y}{\partial w w}$$

$$C_{r r} = \frac{\partial C_Y}{\partial r r}$$

(7)

The ‘$*$’ indicates that the derivatives are to be evaluated at the trim state.

Note the distinct use of the ‘1’ and ‘2’ derivatives in Eqs.(4) through (6). The ‘1’ derivatives refer to the dynamic effect due to the relative angular rate between the body and the wind axes. That is, when the airplane is rotating relative to the wind. The ‘2’ derivatives represent what is called the flow curvature effect. That is, when the airplane is flying along a curved flight path, and the body and wind axis angular rates are identical. For instance, an arbitrary body-axis yaw rate $\Delta \beta_b$ can be split into two components: one equal to the wind-axis yaw rate $\Delta \beta_w$, and another equal to the difference between the two, $(\Delta \beta_b - \Delta \beta_w)$. The first, $(\Delta \beta_b - \Delta \beta_w)$, multiplies the ‘2’ derivative, and the second, $(\Delta \beta_b - \Delta \beta_w)$, multiplies the ‘1’ derivative.
Under small perturbations, we can approximate \(\Delta \mu = \Delta \phi\), the body-axis roll angle, and the relation between the yaw angles and sideslip angle is approximately:

\[
\Delta \chi = \Delta \beta + \Delta \psi \tag{8}
\]

With \(\Delta \mu = \Delta \phi\) and assuming small trim angle of attack \(\alpha^*\), the following approximations hold [5]:

\[
\Delta p_b - \Delta p_w = 0 \quad \text{and} \quad \Delta r_b - \Delta r_w = \Delta \hat{\beta} \tag{9}
\]

\[
\Delta p_w = \Delta \hat{\mu} - \Delta \hat{\chi} \sin \gamma^* = \Delta \hat{\mu} \quad \text{and} \quad \Delta r_w = \Delta \hat{\chi} \cos \gamma^* \cos \Delta \mu = \Delta \hat{\chi} \tag{10}
\]

By the first of Eq.(9), we do not need to distinguish between a body-axis roll rate and a wind-axis roll rate when dealing with small perturbations. Using these approximations in Eq.(4) through Eq.(6), the aerodynamic model may be written as:

\[
\Delta C_Y = C_{Y \beta} \Delta \beta + C_{Y \mu} \Delta \hat{\mu} \left( b/2V^* \right) + C_{Y \chi} \left( -\Delta \hat{\beta} \right) \left( b/2V^* \right)
+ C_{Y \chi} \Delta \hat{\chi} \left( b/2V^* \right)
\]

\[
\Delta C_{l} = C_{l \beta} \Delta \beta + C_{l \mu} \Delta \hat{\mu} \left( b/2V^* \right) + C_{l \chi} \left( -\Delta \hat{\beta} \right) \left( b/2V^* \right)
+ C_{l \chi} \Delta \hat{\chi} \left( b/2V^* \right)
\]

\[
\Delta C_{n} = C_{n \beta} \Delta \beta + C_{n \mu} \Delta \hat{\mu} \left( b/2V^* \right) + C_{n \chi} \left( -\Delta \hat{\beta} \right) \left( b/2V^* \right)
+ C_{n \chi} \Delta \hat{\chi} \left( b/2V^* \right) \tag{11}
\]

where the ‘pI’ derivative terms have dropped out since \(\Delta p_b - \Delta p_w = 0\) as per Eq.(9). Inserting the aerodynamic model of Eq.(11) in Eqs.(1) through Eq.(3) gives the complete set of lateral-directional equations as below:

\[
\Delta \ddot{\chi} = \left( \frac{\bar{g}S}{W} \right) \left[ C_{Y \beta} \Delta \beta + C_{Y \mu} \Delta \hat{\mu} \left( b/2V^* \right) \right] + \Delta \ddot{\chi}
\]

\[
+ C_{Y \chi} \left( -\Delta \hat{\beta} \right) \left( b/2V^* \right) + C_{Y \chi} \Delta \hat{\chi} \left( b/2V^* \right) \right] + \Delta \mu \tag{12}
\]

\[
\Delta \ddot{\mu} = \left( \frac{\bar{g}S}{I_{xx}} \right) \left[ C_{l \beta} \Delta \beta + C_{l \mu} \Delta \hat{\mu} \left( b/2V^* \right) \right]
\]

\[
+ C_{l \chi} \left( -\Delta \hat{\beta} \right) \left( b/2V^* \right) + C_{l \chi} \Delta \hat{\chi} \left( b/2V^* \right) \right] \tag{13}
\]

\[
\Delta \ddot{\psi} = \left( \frac{\bar{g}Sh}{I_{zz}} \right) \left[ C_{n \beta} \Delta \beta + C_{n \mu} \Delta \hat{\mu} \left( b/2V^* \right) \right]
\]

\[
+ C_{n \chi} \left( -\Delta \hat{\beta} \right) \left( b/2V^* \right) + C_{n \chi} \Delta \hat{\chi} \left( b/2V^* \right) \right] \tag{14}
\]

**Timescales**

Three distinct timescales arise from Eqs.(12) through (14) which may be identified as follows:

\[
T_s = \left( \frac{V^*}{g} \right) \sim 10 \text{ sec} \quad T_r = \sqrt{\frac{I_{xx}}{q S b}} \sim 1 \text{ sec} \tag{15}
\]

For a conventional airplane, the slow timescale \(T_s\) is of the order of 10 sec and corresponds to the spiral mode. The intermediate timescale \(T_r\) is of the order of 1 sec and is the scale at which the dutch roll motion is observed. The fast timescale \(T_s\) is of the order of 0.1 sec corresponding to the roll (rate) mode. The clear distinction between these timescales is what allows their corresponding modes to be separated analytically from one another.

**Modal Approximation**

A few reasonable assumptions can be made to obtain approximate expressions to the lateral-directional modal parameters. The rate derivatives of the side force coefficient, \(C_{Y \beta}, \ C_{Y \mu}, \ \text{and} \ C_{Y \chi}\) in Eq.(12) are usually of lesser importance and may be ignored. Likewise, the derivative \(C_{n \mu}\) is usually not significant enough and may be dropped. Following the multiple timescale procedure detailed in our paper, [5] with the appropriate use of static residuals, the following approximations to the roll, dutch roll and spiral mode parameters may be obtained:

**Roll (rate) Mode Eigenvalue :**

\[
\lambda_r = L_{p2} \tag{16}
\]

**Dutch Roll Frequency and Damping** :

\[
\omega_{nDR}^2 = N_{\beta} + \left( \frac{g}{V^*} \right) Y_{\beta} N_{r2} + \left( \frac{L_{\beta}}{L_{p2}} \right) \tag{17}
\]

\[
2 \kappa_{nDR} \omega_{nDR} = -N_{r1} - \left( \frac{g}{V^*} \right) Y_{\beta} + \left( \frac{L_{r1}}{L_{p2}} \right) \tag{18}
\]
Spiral Mode Eigenvalue :

\[
\lambda_s = \frac{\bar{q}}{V^*} \left[ \frac{L_{\bar{p}} N_{r2} - N_{\bar{p}} L_{r2}}{\lambda_r \theta_{nDR}^2} \right]
\]

(19)

where the symbols stand for :

\[
\left[ \frac{q S b}{W} \right] C_{\bar{p}b} = Y_{\bar{p}}; \left[ \frac{q S b}{I_{zz}} \right] C_n \beta = N_{r1}; \left[ \frac{q S b}{I_{xx}} \right] C_n = L_{r1}; \left[ \frac{q S b}{2V} \right] C_{I_{l2}} = L_{r2}.
\]

(20)

Stability Criteria

Replacing the symbols from Eq.(20) in Eqs.(16) through Eq.(19), we can obtain stability criteria for the modes in terms of the aerodynamic derivatives. For simplicity, the term \( Y_{\bar{p}} \) in Eqs.(17) and (18) has been neglected.

Roll (rate) Mode :

\[
C_{l\bar{p}2} < 0
\]

(21)

Dutch Roll Mode :

Stiffness :

\[
C_{n\beta} + \varepsilon \left( C_{l\bar{p}2} / C_{l\bar{p}2} \right) > 0
\]

(22)

Damping :

\[
C_{n r1} + \varepsilon \left( C_{l r2} / C_{l r2} \right) < 0
\]

(23)

Spiral Mode :

\[
C_{l \bar{p}} C_{n r2} - C_{n \beta} C_{l r2} > 0
\]

(24)

In Eqs.(22) and (23), \( \varepsilon \) is a dimensionless ratio of the various timescales as follows :

\[
\varepsilon = T_f / T_s T_r
\]

(25)

For a conventional airplane, since \( T_f \sim 1 \) sec, \( T_s \sim 10 \) sec, and \( T_r \sim 0.1 \) sec, as given in Eq.(15), \( \varepsilon \sim 1 \).

For Conventional Full Scale Airplanes

Let us examine the various aerodynamic derivatives that appear in Eqs.(21) through (24), first for conventional "full" scale airplanes.

- \( C_{l\bar{p}2} \) : Usually called the "roll damping" derivative, this is essentially the same as the traditional derivative \( C_{l\bar{p}} \). The main contribution comes from the wing. There is also a small contribution from the horizontal and vertical tails. For cruciform missile configurations with no wing, the tail provides all the roll damping. Typically, \( C_{l\bar{p}2} < 0 \) may be expected, hence the stability of the roll mode is rarely an issue.

- \( C_{n\beta} \) : This is a significant contributor to the yaw (dutch roll) stiffness and is obtained chiefly from the vertical tail. Generally, \( C_{n\beta} (vertical \ tail) > 0 \). There may be a small negative contribution from the fuselage and other components. As can be seen from Eqs.(21) through (24), \( C_{n\beta} \) alone does not determine the stability of any of the modes though it does play a major role in dutch roll stiffness as well as the spiral eigenvalue.

- \( C_{l\bar{p}} \) : Sometimes called the "dihedral derivative", \( C_{l\bar{p}} \) is obtained largely from wing dihedral and wing sweep. There are lesser contributions from the vertical tail, horizontal tail dihedral, and wing position on the fuselage. Normally, \( C_{l\bar{p}} < 0 \), and the effect due to wing sweep increases with angle of attack. As for \( C_{l\bar{p}} \), \( C_{l\bar{p}} \) alone does not determine the stability of any of the modes though it figures in dutch roll stiffness as well as the spiral eigenvalue.

- \( C_{n r1}, C_{l r1} \) : These correspond to the traditional derivatives \( C_{n r}, C_{l r} \), respectively. Often, \( C_{n r1} \) is called the "yaw damping" derivative, though as seen in Eq.(23), it is the combination of the two that determines yaw (dutch roll) damping. Both the wing and the vertical tail contribute to these two derivatives and their efforts usually reinforce each other. Normally, one would expect \( C_{n r1} < 0 \) and \( C_{l r1} > 0 \). The contribution of the horizontal tail is usually minor.

- \( C_{n r2}, C_{l r2} \) : These are the flow curvature derivatives and come into play when the airplane follows a curved (turning) flight path in yaw. For the wing, these arise because the wing half on the outside of the turn must travel at a higher velocity than the half on the inside of the turn. A similar effect may be expected from any component that is laterally displaced from the aircraft...
plane of symmetry which contains the center of gravity (CG). The effect from the horizontal tail is usually less significant due to its limited span. Typically, $C_{nr2} < 0$ and $C_{lr2} > 0$. The important point is that the vertical tail has no contribution to these derivatives as long as it lies in the said plane of symmetry, as the entire vertical tail sees the same relative velocity as the velocity at the CG. For a twin vertical tail, however, the tail on the outside of the turn will see a higher velocity and that on the inside of the turn will experience a lower velocity than the velocity at the CG. This will create a drag differential that causes a yawing moment with $C_{nr2} < 0$, that is, in the same sense as the effect due to the wing.

On the basis of this discussion, we can write down the typical signs of the various derivatives in Eqs. (21) through (24) and examine whether each stability criterion is usually met for a conventional airplane configuration. The usual sign of each derivative is marked under it in the following. Also, derivatives where the vertical tail has a predominant influence or a reasonable effect are marked with a bar over them.

**Roll (rate) Mode**:  
$$C_{lp2} < 0$$  
(−)  
(26)

**Dutch Roll Mode**:  

**Stiffness**:  
$$\widetilde{C}_{n\beta} + \varepsilon \frac{(C_{lp2})}{(C_{lp2})} > 0$$  
(+)

**Damping**:  
$$\widetilde{C}_{nr1} + \varepsilon \frac{(C_{lr1})}{(C_{lp2})} < 0$$  
(−)  
(28)

**Spiral Mode**:  
$$C_{\beta} C_{nr2} - C_{\beta} C_{lr2} > 0$$  
(-)  
(-)  
(+)(+)  
(29)

Note that $\varepsilon$ from Eq.(25) is of the order of 1.

- From Eq.(26), the roll mode stability is virtually guaranteed by the wing itself.
- Looking at Eq.(27), both terms contribute to the yaw stiffness - the first is mainly due to the vertical tail, the second is primarily from the wing. Even without a vertical tail (first term missing), with a sufficiently negative $C_{n\beta}$ (wing dihedral and sweep), yaw stiffness can be ensured.
- From Eq.(28), again each of the two terms is negative and ensures yaw damping. The vertical tail is a part contributor to the two derivatives with over-bars. Even without the vertical tail, the wing contribution to each of these two derivatives provides yaw damping.
- For the spiral mode eigenvalue in Eq.(29) alone, the two terms oppose each other. The net result is the difference between two positive terms and can go either way. Notably, the vertical tail contributes dominantly to only one of the four derivatives that go into Eq.(29). If the vertical tail is deleted, only the first term remains in Eq.(29) and it comfortably assures a stable spiral mode!

The conclusion is that the vertical tail is not necessary for the stability of any of the lateral-directional modes. As long as the wing can contribute sufficient $C_{n\beta}$, and a large enough $C_{nr1}, C_{lr1}$, yaw stiffness and damping can be managed. And without the vertical tail, spiral mode stability is no longer in question.

With no vertical tail, the rudder would also be absent, and the issue of alternative sources of directional control arises. Typically, the use of roll and pitch control devices does produce some yawing moment; hence they may be employed as surrogate yaw control devices. The use of asymmetric wing dihedral as a yaw control on airplanes without a vertical tail has been proposed [12,13]. The mechanism is apparently similar to that used by birds with their tail. Winglets, which are now ubiquitous on airplanes, could provide another source of yaw stability and control [14].

**For Birds and Small Scale Airplanes**

First of all, we need to establish the scaling relation between the flight of “full” scale airplanes and that of birds and small scale airplanes. The variety of flight over the range of Reynolds numbers is depicted in Fig.2. When compared to “full” scale airplanes, we scale down the following variables by the respective order indicated to get to small scale or bird flight scale.

- Scale down by 1 order: Flight velocity $(V)$, wing chord $(c)$, vehicle height $(h)$
- Scale down by 2 orders: Wing span $(b)$, vehicle length $(l)$
Thus, the Reynolds number which is defined as
\[ \text{Re} = \frac{\rho V l}{\mu}, \]
where \( \rho, \mu \) are the air density and viscosity, respectively, scales down by 3 orders (1 from \( V \), 2 from \( l \)). This agrees with Fig. 2 which shows general aviation and jet aircraft at \( \text{Re} \sim 10^7-10^8 \) and birds and model airplanes 3 orders lower at \( \text{Re} \sim 10^4-10^5 \). At this lower range of Reynolds number also the aerodynamic model in Eqs. (4) through (6) and Eq. (11) is applicable, hence the lateral-directional equations in Eqs. (12) through (14) may be used for the analysis.

Next, examining the timescales in Eq. (15),

- The slow timescale \( T_s \) scales down by 1 order because of \( V \).
- For the intermediate timescale \( T_f \), we must consider the factors in the numerator and denominator. Each of their terms scales down by the order indicated in the parenthesis after them: \( I_{zz} \) (by 9 orders, since mass scales down as volume by 5 orders (\( b.l.h \sim 2.2.1 \)), and the two lengths perpendicular to the Z axis, wing span and vehicle length, scale down by 2 orders each), \( q \) (by 2 orders), \( b \) (by 2 orders), and \( S \) (by 3 orders, 2 for \( b \) and 1 for \( c \)). Thus, the numerator scales down by 9 orders and the denominator by 7, the difference is 2 orders, and after taking the square root, \( T_f \) scales down by 1 order.
- The fast timescale \( T_r \) scales down by 1 order (2 for \( b \) minus 1 for \( V \)).

Thus, the timescales at the bird flight and small airplane flight scale are arranged as:

\[
T_s = \frac{V^*}{g} \sim 1 \text{ sec } ; T_f = \sqrt{\frac{I_{zz}}{q S b}} \sim 0.1 \text{ sec } ;
\]

\[
T_r = \frac{b}{2V^*} \sim 0.01 \text{ sec } \quad (30)
\]

Compared to the timescales for "full" scale airplanes in Eq. (15), each of the timescales in Eq. (30) is 1 order faster. However, the relative difference in timescales between the three of them is maintained. Hence the modal approximation based on the multiple timescale procedure [5] holds, and the relations for the roll, dutch roll and spiral mode parameters in Eqs. (16) through (19) remain valid. Consequently, the stability criteria in Eqs. (21) through (24) also hold true for bird/small scale aircraft flight. As per the timescales in Eq. (30), the factor \( \epsilon \) in Eq. (25) again works out to be of the order of 1. Hence, the discussion in Section - For Conventional "Full" Scale Airplanes, for "full" scale airplanes holds entirely for bird/small scale airplane flight as well. The conclusion, therefore, is the same - birds need no vertical tail as nature has amply demonstrated, nor do small scale airplanes. It is not a matter of scale but a verity that holds across the spectrum.

**Conclusion**

By carefully examining the correct modal approximations to the roll, dutch roll and spiral modes, it has been conclusively established that the vertical tail is not essential for the stability of any of the lateral-directional modes. This is true at all scales from bird/small scale airplane flight to conventional full scale aircraft. An appreciation of this fact will hopefully trigger the next revolution in airplane configuration design - vertical-tailless aircraft.

**References**


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**Fig.1** A B-52 that Managed to Fly Safely Despite the Almost Total Loss of its Vertical Tail

**Fig.2** Flight Over the Range of Reynolds Numbers (from Ref.15)