The Principles of the Constant ‘g’ Stability System

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OVERVIEW

Constant ‘g’ flight stability is a feedback system that detects changes in vertical acceleration resulting in geometrical changes to produce a restoring moment. Nature has evolved this method independently three times to create pterosaurs, birds, and bats. The object of this paper is to describe the system principles and also describes variations not found in Nature. Constant ‘g’ and geometrical stability are compared and three manned aircraft designs are presented which benefit from the constant ‘g’ stability system.

1. Definition

Constant ‘g’ stability is a mechanical feedback system and is the basis for longitudinal stability of the three flying genera found in Nature. It detects lift changes and causes the configuration to change to produce a restoring moment.

1.2. Paper Contents

1. Introduction - Stability about constant vertical acceleration
2. Muscle tension and lift forces
3. Stability and wing folding
4. Nature’s versus geometrical stability
5. Control with Constant ‘g’ Stability
6. Control of roll and yaw
7. Flexible wing stability analysis
8. Inertia effects and stability
9. Alternate variations not found in Nature
10. Summary
11. References

1.3. Constant Vertical Acceleration

Aircraft are designed to be stable about a <u>constant angle of attack.</u> Vertebrate flyers are stable about a <u>constant vertical acceleration</u>. They compare muscle tension with air loads and their wings twist and sweep to produce a restoring moment. It is a mechanical feedback system.

1.4. Accelerometer Based Pitch Stability

In Nature, all birds, bats, and pterosaurs achieve longitudinal stability through a system that takes advantage of their flexible wing structure and forward swept wings. It is a feedback system based on changes in vertical acceleration, comparing muscle tension with flight loads.

1.5. FLEXIBLE WINGS THAT TWIST

A change in wing lift causes the swept forward wing tips to twist producing a restoring moment. This allows a cambered wing-only configuration, the system maintaining a state of unstable equilibrium.

1.6. Flexible Wings That Sweep

A change in wing lift also causes the wing tips to alter its sweep to produce a restoring moment. With a reduction in lift, the humerus rotates forward, slightly extending the wing, sweeping forward and reducing twist.

In flapping flight, on the downstroke, the flight muscle contracts, extending and twisting the wing for forward thrust. Thus the stability system also enhances the flapping cycle.

Wing Planforms in Nature

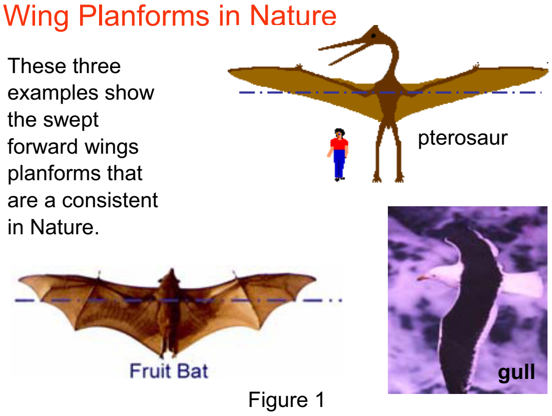


Figure 1

Aerofoil Balance At Equilibrium

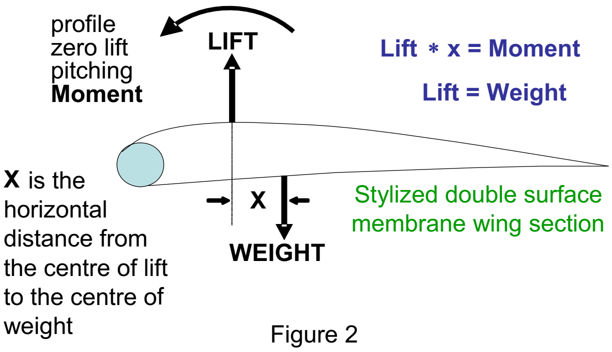


Figure 2

Stability Graph

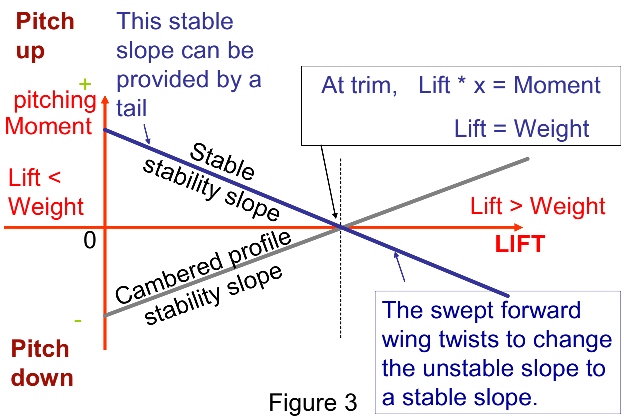


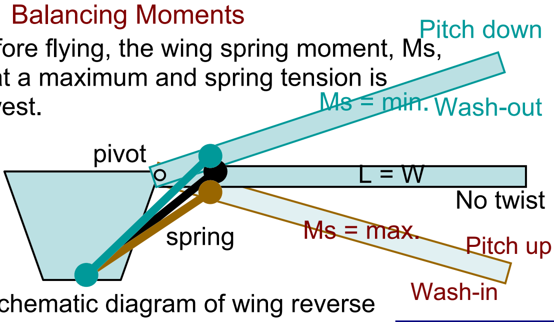
Figure 3

2. Muscle Tension & Lift Forces

Natural elasticity causes a flight muscle to act as a spring, thus lift a moment is balanced by a spring moment.

2.1 Balancing Moments

Before flying, the wing spring moment, Ms, is at a maximum and spring tension is lowest.



Schematic diagram of wing reverse gradientem

There is only one point where balance is achieved.

Stability is maintained during flapping flight

Figure 4

If lift decreases, the wing will start to descend. To regain its original flight path, it will have to develop more lift than weight and thus a higher spring moment. At the same time as seen in figure 4, the spring tension will have decreased. The only way to regain the original flight path is for the spring moment to increase as lift decreases. **This is a reverse gradient spring moment**.

A flying creature is displaced upward from a desired horizontal flight path:

- If L>W, lift needs to be less than weight to return to its desired flight path.
- If L<W, lift needs to be greater than weight if altitude is to be regained

Flight muscles resist wing bending moments and their elasticity means they also act as springs.

When lift increases, causing the creature to rise:

- The muscle tension moment needs to decrease if this height gain is to be lost
- The restoring moment must decrease as the muscle is extended as a spring.

A reverse gradient spring rate is required

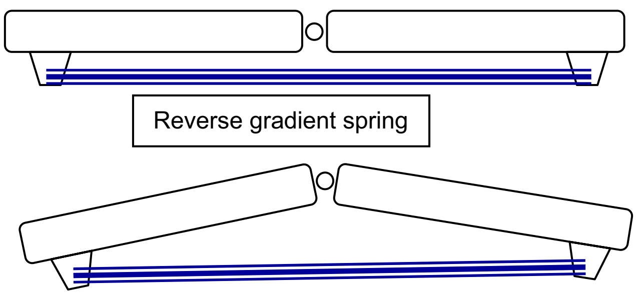


Figure 5

- In nature the reverse gradient spring is always due to wing joint geometry.
- There are many variations to achieve a reverse gradient spring rate.

As hinge bends, spring distance from pivot increases

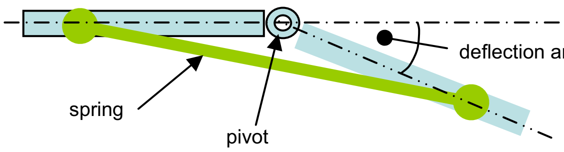


Figure 7

A is breastbone	**Formulas**
moment arm	ac = side_c * sin(A)
A to moment arm end	bc = side_c * cos(A)
humerus	C = asin(ac/c)
moment arm end to C	ba = side_a * cos[C]
spring length	Ls = bc + ba
spring extention	dLs = Ls - Lso
spring tension	Ts = dLs * ks
spring moment	M = Ts * ac
pivot	B = 180 - (A + C)

Table 1

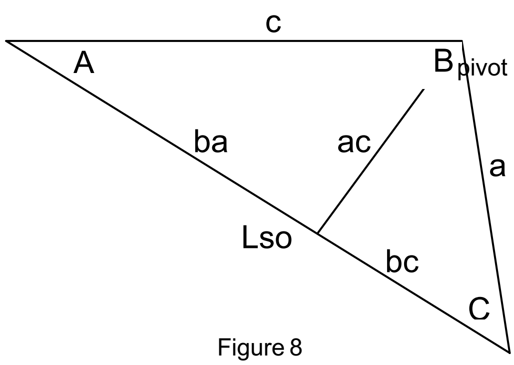


Figure 8

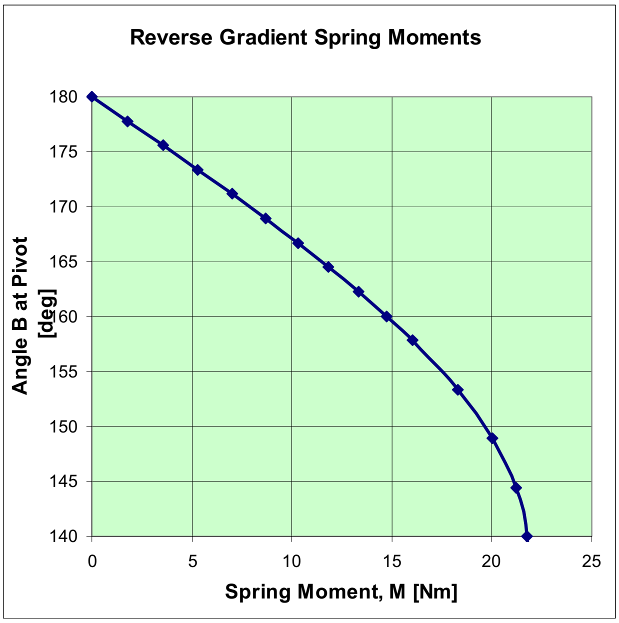


Figure 9

3.1 STABILITY AND FOLDING WINGS

In Nature, wing folding enhances both stability and flapping flight. Wing geometry is arranged such that lift forces extend the wing. A consequence of this is that a wing will extend and retract slightly with changes of lift.

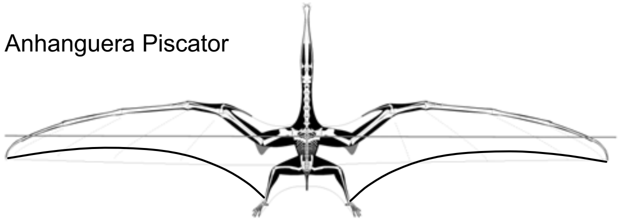


Figure 10

The arrangement of muscles and tendons must resolve aerodynamic forces.

The Anhanguera pterosaur was too large at 5.5 m span to flap its wings. It achieved its stability through a reverse gradient linkage between its humerus and breast bone (red). A lift increase caused its humerus to hinge back, reducing membrane tension for a pitch down effect.

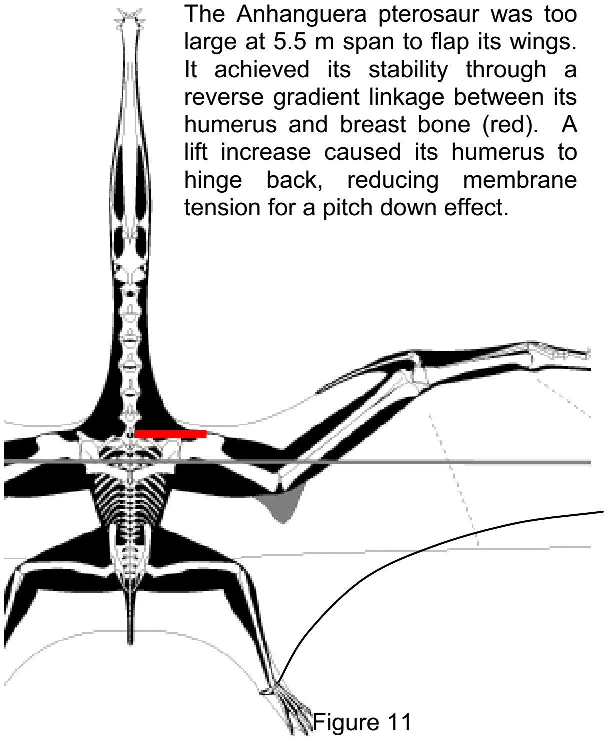


Figure 11

Wing joints all have some degree of movement. For the wing joint movement to affect stability, forces must vary as a result of lift change. For stability to be increased, a reverse gradient spring linkage must exist.

3.2 STABILITY AND FLAPPING FLIGHT

The constant 'g' stability principles must apply throughout the wing flapping cycle. This involves large changes of the magnitude and direction of air forces. The stability system detects changes whereby the flight muscle is acting as a spring. This happens at the same time as the flight muscles are being flexed during flapping flight.

3.3 EXAMPLE FROM NATURE

Figure 12 shows a Quetzalcoatlus humerus pivoting on its shoulder joint (yellow) in response to changing flight loads. Here the reverse gradient muscle moment is clearly illustrated as the muscle lever arm alters with humerus position

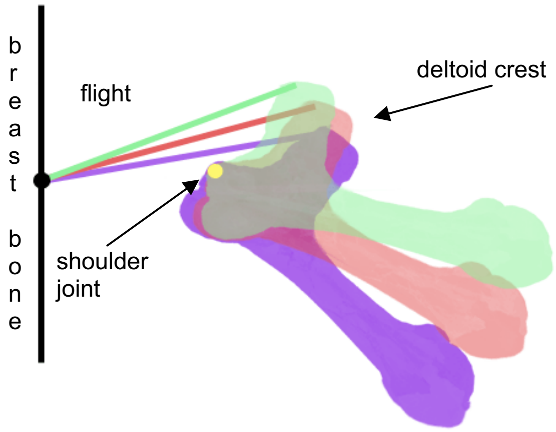
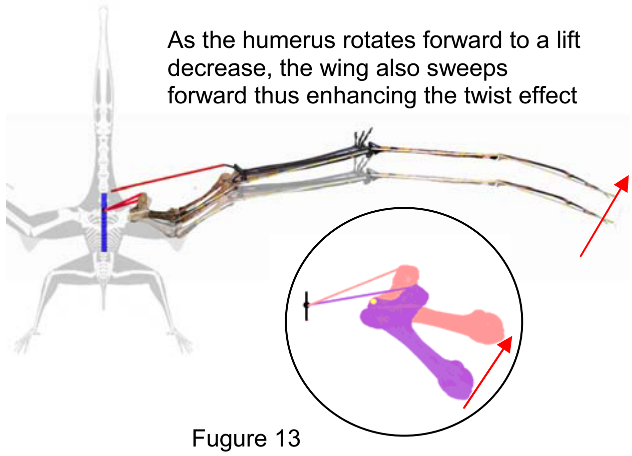


Figure 12

The deltoid crest is a feature of all vertebrate flyers. In the case of pterosaurs, the flight muscles resist backward rotation of the humerus due to membrane tension. An increase in lift causes the humerus to rotate backwards. This causes the wing to fold slightly, increasing wing twist and decreasing sweep for a correcting pitch down moment.



Fugure 13

The ultimate test of stability is the question: "Is there a pitch up moment at zero net lift?" The combined pitch up moments must be balanced against the pitch down moment due to wing camber.

3.4 STABILITY LIMITS

Stability cannot be increased beyond the point where the system reaches its mechanical limits before equilibrium is reached. The following factors influence stability:

1. The available range of humerus rotation is about ± 10º if the reverse gradient muscle moment is to be sustained.
2. A soft spring maximises the reverse gradient spring moment and extends its angular range.
3. Spring attachment points are equal distances from the pivot point.
4. Wing twist range
5. Wing sweep angle
6. Wing aerofoil camber

For a fixed camber wing, the range of twist and sweep angles are the critical factors controlling Constant 'g' Stability.

4. COMPARING NATURE'S STABILITY WITH GEOMETRICAL STABILITY

Nature's pitch stability differs from geometrical in that it compares an aerodynamic moment with a muscle moment. A mechanical feedback system works to equalise the muscle and aerodynamic force moments. In this case, the elasticity of a flight muscle causes it to act as a spring.

The feedback balances two unstable gradients to maintain an unstable equilibrium. The two gradients are a cambered wing profile and a reverse gradient spring moment. Automatic feedback mechanisms are found throughout Nature as are reverse gradient muscle moments. Thus the evolution of a mechanical feedback mechanism to ensure flight stability is consistent with the way Nature works in general.

Nature's Design	**Man's Design**

• Flexible wings
• Detects lift changes
• Compares
  – wing bending moment
  – Flight muscle tension
• No tail needed
• Allows cambered wing profile
	• Fixed geometry
	• Detects angle of attack changes
	• Requires one or all of
	  – A tail
	  – Swept wing with twist
	  – Reflex or S shaped wing section
	• Cambered wing difficult if no tail

• Vertebrate flyers are stable about a **constant vertical acceleration**.
• The system compares muscle tension to air loads
  • Their wings twist to produce a restoring moment.
  • It is a mechanical feedback system based on changes in vertical accelerations.
	Aircraft are designed to be stable about a **constant angle of attack**.
	• This is achieved by setting a foreplane at a larger angle of incidence then a tailplane.
	• Stability occurs through proportional changes in angles of attack between foreplane and afterplane.

Maintaining Flight Path	

• A steady flight path in turbulent air needs no pilot input
  • Needs no attention from pilot
  • Stability about constant vertical acceleration.
  • Low wing lift curve slope
	• In turbulent air, an aircraft tries to maintain a constant angle of attack resulting in an unsteady and bumpy flight path
	• High pilot work load

Gust Loading	

Inherent wing bending relief
  • The system will not accept loads greater than manoeuvre 'g' setting.
  • Swept forward wings shed excess load at the wingtips.
	Rigid wings cannot flex to shed excess loads.
	• Bumpy flight
	• Increased structural strength and weight required.

Equilibrium	
Unstable	Stable
Stability versus Manoeuvrability	
No conflict	Trade-off
Control	
Adjust system parameters	Move control surfaces
Structure Weight	
Wing stressed for manoeuvre only • Wing only • Short fuselage	Wing stressed for gusts • Weight of horizontal and vertical tail • Weight of long fuselage
Vertical Tail	
No vertical tail if correct planform	Vertical tail + rudder

Table 2

5. CONTROL WITH CONSTANT 'g' STABILITY

Controls for a pilot flying a craft with constant 'g' stability differ slightly from those of conventional aircraft. Since constant 'g' stability maintains equilibrium about a constant vertical acceleration, maintaining level flight is an automatic action and requires no input from a pilot.

5.1 TRIM SPEED

The system will seek balance where:

Lift × X = Moment

Lift = [vertical acceleration] g × Weight

Θ = gliding angle = ATAN (D/L)

D = total drag at flying speed, V

X = dist. From Lift to Weight

S = total wing area

c = mean aerodynamic chord

M = pitching moment

$= \rho/2 \times V^2 \times S \times c \times C_m$

C_m = pitching moment coefficient

$W \times g \times X = \rho/2 \times V^2 \times S \times c \times C_m$

Solving for V

$$\mathbf{V = SQRT\{(2 \times W \times g \times \cos(\theta) / S \times c \times C_m\}}$$

Thus, for any given wing camber, there is only one speed for which the wing is in balance. If the wing is powered then gliding angle, θ represents the net result of drag and thrust. To make a steep landing approach an element of drag must be available.

5.2 Examples Of Using Constant 'G' Controls

5.2.1 Approach to Landing

- Set air brake for desired descent angle
- Set wing camber for approach speed
- Set spring control for g = 1

5.2.2 Level Flight

- Set air brake to off
- Set wing camber for flight speed
- Set spring control for g = 1

5.2.3 Circling Flight

- Set air brake to off
- Set wing camber for circling speed
- Set spring control for bank angle

5.3 Inherent Autopilot

There is no phugoid motion since there is no pendulum effect and airspeed is held constant. Only heading has to be maintained for cross country flying. Similarly for circling flight, the system will maintain a constant vertical acceleration. In effect, a pilot does not control his craft directly; he gives it instructions.

A pilot manoeuvres through adjusting the parameters of the stability system and not through control movement. Thus the pilot's controls are not connected to control surfaces; they are connected to a mechanism that adjusts a spring moment.

5.4 No Conflict Between Stability And Control

There is no design trade-off between stability and control with the Constant 'g' System. Unstable equilibrium means that the system will move to a new balance point with only a gentle impulse.

5.4. AUTOMATIC POWER ASSISTED CONTROLS

There is also automatic servo assistance for control operations. The system maintains a state of unstable equilibrium and once system parameters are changed to execute a manoeuvre, the inherent instability powers the change. With geometric stability any manoeuvre must act against system stability.

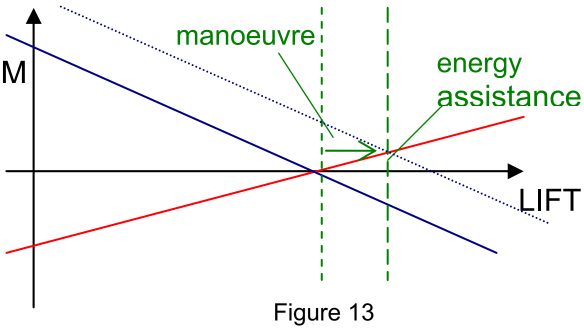


Figure 13

6.1 Stability and Control in Roll and Direction

Nature's flyers have no vertical tails. They achieve directional stability through their wing shapes. The basic formula is a wing whose centre section has forward sweep and dihedral and an outer section with sweep back and dihedral

Directional control is through differential wing twist. There is much less air resistance in yaw than in roll and so differential wing twist yaws first. Thus, a turn is initiated by twisting the wings in opposite directions. Once the wing begins to turn, the inner wing is moving more slowly and the wing will begin to roll.

6.2 Typical Planform of a vertebrate wing

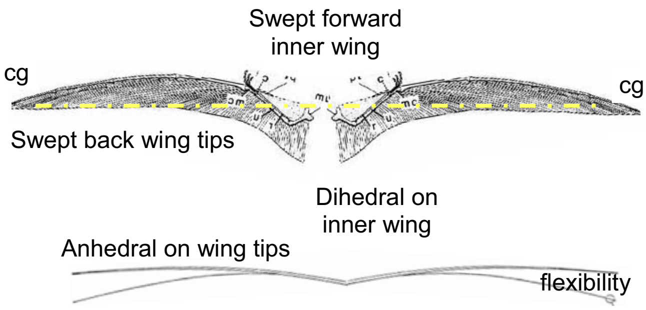


Figure 14

6.3 Directional Stability of Pterosaurs with Large Heads

Many pterosaurs had long necks and large heads, often with a pronounced crest. Their heads pivoted on a ball joint at the end of their long necks. The head centre of gravity was ahead of the neck joint and In destabilising yaw, head inertia caused the head to swivel to create a restoring yawing moment.

7.1 Wing Design Spreadsheet

With a spreadsheet, the stability of a flexible wing can be analysed. First, the following variables are set:

- pilot weight
- structure weight
- air mass density
- landing airspeed
- maximum lift coefficient
- wing span
- max spar bow
- sweep angle
- dihedral angle
- trailing edge shape factor
- profile zero lift pitching moment
- twist angle
- wing lift slope
- circling speed, Vc

From This Information, The Following Are Calculated:

- wing area
- aspect ratio
- root chord
- mean aerodynamic chord
- X position of mean aerodynamic centre, MAC
- wing loading
- wing pitching moment for thermaling speed
- average wing thermaling lift coefficient
- angle of attack at Vc from 0 lift angle

From this information spreadsheets enable:

- An elliptical wing planform to be defined
- the wing sweep to be plotted
- variations of planform shape to be evaluated
- stability to be evaluated by allowing the wing to twist and sweep as the wing incidence is varied.

7.2 EXAMPLE OF WING DATA INPUT

Input

			units
➢ pilot weight	Wp	75	kg
➢ structure weight	Ws	25	kg
➢ air mass density	ro	1.22	kg/m³
➢ landing airspeed	v	7.35	m/s
➢ maximum lift coefficient	CL_{max}	2	
➢ wing span	b	11.0	m
➢ max spar bow	z	0.3	m
➢ sweep angle	L	15	deg
➢ dihedral angle	g	2	deg
➢ profile pitching moment	Cm_o	-0.2	
➢ twist angle	twist	0	deg
➢ TE shape factor	shp	0.3	
➢ wing lift slope	dCLa	0.089	
➢ circling speed	Vc	11	m/s

Calculate

			units
➢ wing area	S	14.9	m²
➢ aspect ratio	AR	8.1	
➢ root chord	Cr	1.75	m
➢ mean chord	Y-MAC	1.49	m
➢ X position of MAC	X-MAC	2.75	m
➢ wing loading	WL	66	N/m²
➢ avg. circling CL	CL	0.89	
➢ AoA at Vc	AoA	10.0	deg
➢ wing Cmo at Vc	Mc	0.90	
➢ Lift pitching moment	ML	327	Nm
➢ Net pitching moment	M	0.33	Nm

7.3 Defining A Stable Wing Planform

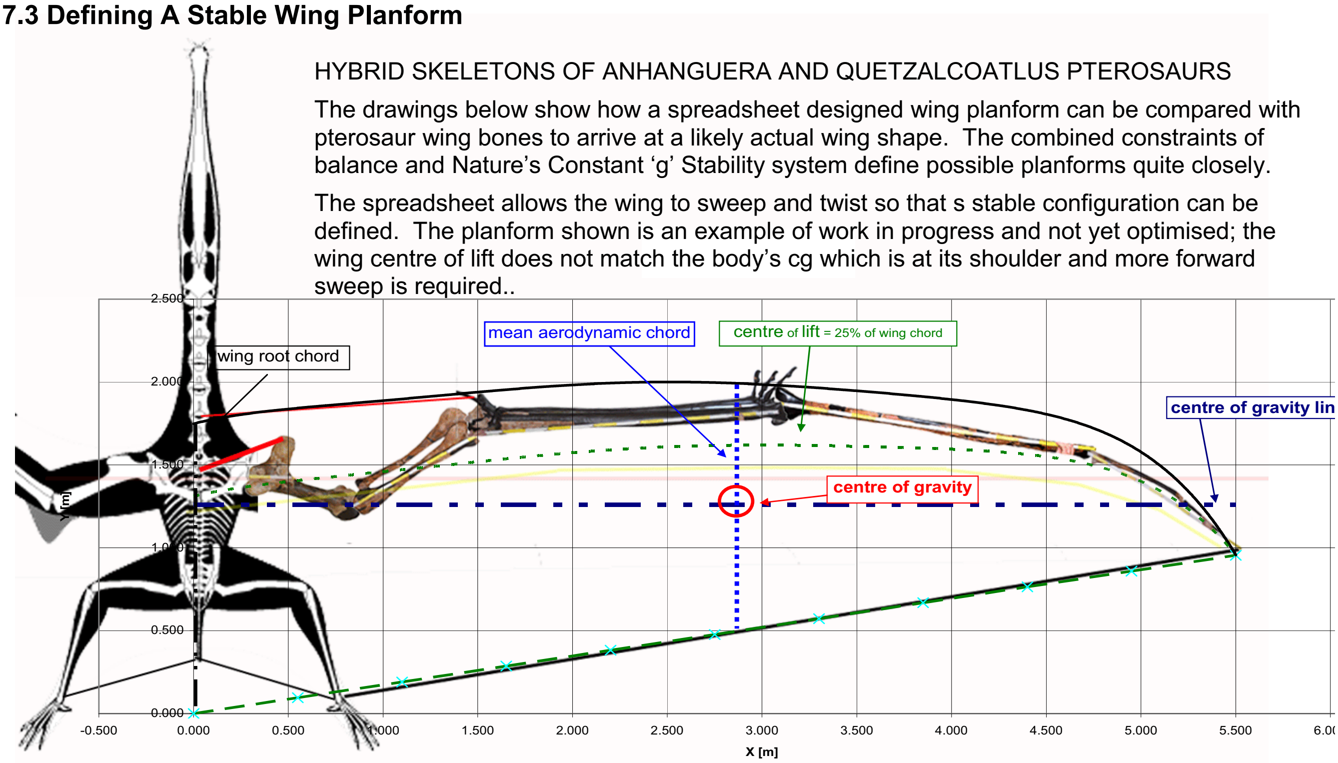


Figure 15

8. Inertial Effects

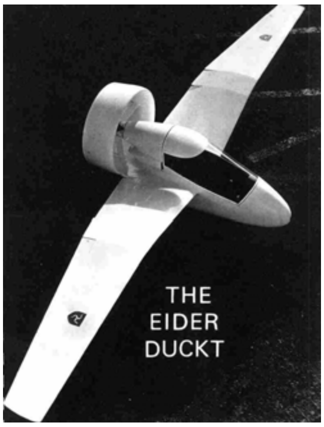
The Constant ‘g’ Stability system maintains a state of unstable equilibrium and pitch change tends to occur so rapidly that inertia effects need to be considered. In Nature, the unstable wing rotates about a stable body of relatively high inertia.

For example, a decrease in wing lift will cause the wing to pitch down. The body’s inertia resists this rapid rotation about the shoulder joint which causes the humerus to pivot such that the pteroid crest of the humerus moves closer to the breastbone. This then causes the wing to extend and sweep forward slightly producing a correcting pitch up moment. Thus, inertia effects contribute to longitudinal stability.

9. Alternate Variations Not Found In Nature: – Hybrid Rigid Winged Aircraft

9.1 Eider Duckt

The Eider Duckt is a short tailed single seat low powered aircraft. For pitch stability it can use either geometrical or Constant ‘g’, or a hybrid of the two systems.



If using Constant ‘g’, either the elevator in the duct or the inner wing flap can be used for trim balance.

The outer wing panels can be hinged to detect changes of vertical acceleration. This arrangement permits the use of a standard glider aerofoil.

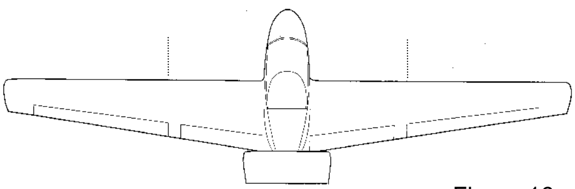


Figure 16

9.2 Aquaduckt Adaptive Craft

Like the Eider Duckt, the Aquaduckt can be configured to use either geometrical or Constant ‘g’ Stability. With

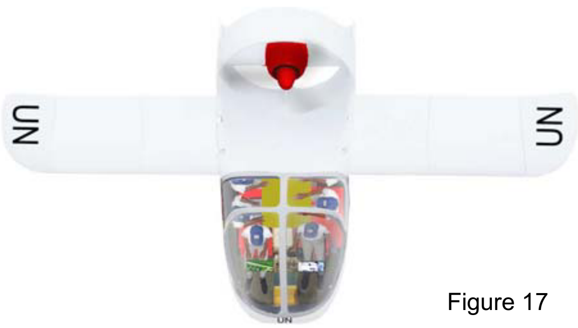


Figure 17

geometrical stability the aircraft flies as a canard with the body playing the role of the foreplane. With Constant ‘g’ Stability, it operates as an enhanced canard. Hinged wing tips detect changes of vertical acceleration and activate wing flaps.

The Aquaduckt has a lifting body with a low lift slope. The camber changing flaps increase the wing’s lift slope and enhance the existing geometrical stability. Introducing Constant ‘g’ Stability enables the aircraft’s centre of gravity to move aft to balance a cambered wing.

9.3 Zealwee Sailplane

The Zealwee is short tailed with swept forward wings.

Figure 18

The wing tips are hinged so that they move up and down with changes of lift relative to the wing. They are connected to ailerons such that a lift increase causes the aileron to deflect upwards. This gives the effect of wing twist on a rigid wing and contributes to a low wing lift slope and bending relief.

10. Summary

Constant ‘g’ Stability is the longitudinal stability system found in Nature among vertebrate flyers.

It is a mechanical feedback system based on comparing muscle or spring tension with aerodynamic moments. Key elements are a reverse gradient spring and wings that change their twist and sweep to produce a restoring moment.

It introduces new possibilities for aircraft design enabling tailless configurations with high lift cambered wings.

11. References

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