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AIRCRAFT LANDING - A TOTAL SYSTEMS APPROACH.

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Abstract

This paper describes the developments made so far in the design and development of an auto-land system for optimising aircraft landing performance. The system takes into account the all-axes aerodynamic and mechanical behaviour of the aircraft at the point of touchdown and landing. The aim is to develop a system that automatically applies the control action to the appropriate aerodynamic and braking systems causing the aircraft to come to rest in an optimal and controlled manner, taking into account weather and runway conditions. The new controller will use main wheel braking from the moment the main gear contacts the runway surface and the wheel velocities match that of the ground. The controller will command the ailerons and main wheel brakes to aid in braking and the ailerons, rudder, nose wheel steering and differential braking to maintain directional stability. A non-linear simulation of a Boeing 747 has been used as a test bed. The paper will describe the theory, rationale and test results received from the non-linear test bed.

Introduction

Auto-land and simple anti-skid braking systems have existed for a number of years. Modern control theory has been extensively used for auto-pilots/ auto stabilisation systems to optimise the in flight behaviour of the aircraft. This is not the case with aircraft braking systems. This paper describes the development of the rationale behind an auto-land system that takes account of the all-axis aerodynamic and mechanical behaviour of the aircraft at the point of touchdown and landing and optimises performance. The system automatically applies the control action to the appropriate aerodynamic and braking systems to cause the aircraft to come to rest in an optimal and controlled manner, taking into account weather and runway conditions. A non-linear simulation of a Boeing 747 has been used as a test bed.

When an aircraft lands, the first means of braking is aerodynamic. In general when the main wheels come in contact with the ground, in order to make full benefit of the aerodynamic braking (drag) force the aircraft is kept at a high angle of attack. Once the nose wheels touch the ground main wheel braking and reverse thrust commences.

During two-point aerodynamic braking full deployment of brake spoilers and flaps has already been selected. While the rudder provides directional stability the elevator is used to hold the aircraft at a high angle of attack until it is necessary to lower the nose so as to avoid bringing the nose down hard. At this point the ailerons are used to keep the wings level. Main wheel braking has not started yet and neither has reverse thrust.

Once the nose gear touches the ground, nose wheel steering, rudder control and differential braking control directional stability. Main wheel braking is employed to retard the aircraft speed still further until a safe taxi speed is attained. Bad runway conditions (icy or wet conditions) make wheel locking a problem. Anti-skid systems are employed that monitor wheel angular rate to prevent or minimise skidding due to a wheel lockup.

The new controller uses main wheel braking from the moment the main gear contacts the runway surface and the wheel velocities match that of the ground. The controller commands the ailerons and main wheel brakes to aid in braking and the ailerons, rudder, nose wheel steering and differential braking to maintain directional stability.

Landing

A landing can be broken up into various different stages. The landing stages that are of interest for this project are from the moment the two main gears touch the runway surface (two point aerodynamic braking), bringing the nose gear down, maintaining directional heading and minimising runway lateral off-set and finally bringing the aircraft down to a safe taxi speed. There are different ways to attempt to control each individual stage. Reference (1) and (2) describe two similar options used with fighter and transport aircraft for minimising lateral runway offset incorporating either rudder control and differential braking or rudder and nose wheel steering. Reference (3) describes advances in anti skid systems to minimise loss of control due to a skidding gear for the 757 and the 767. Other programs look at gaining further data for each runway so as to have a better understanding of the environment that an aircraft will be in contact with. Reference (4) describes such a program that is involved in measuring runway friction coefficient. In January of 1996 Flight international published an article titled "Scientists get to grips with friction testing" describing in brief this project (5). The projects all have common ground. Each project attempts to improve the anti-skid characteristics using the same techniques that have been used in the past but by adding complexity and additional attributes to them. Non have had an attempt at changing the procedure or the controls that are used to optimise the landing phase. Here is a different approach. Ailerons are used to control the friction force on the tires by varying the normal loading on the gears. The ailerons can be used to balance the friction force or can be used to make it favourable towards the port or starboard sides depending on the lateral offset, friction coefficient differential, wind heading or deviation from the runway heading.

Aileron Brake Augmentation.

Using ailerons to increase the normal loading on the legs with the lesser friction force (skidding leg) along with lowering the brake pressure of the leg with the higher friction force gives a slightly higher braking force than the anti-skid system alone. The aileron controller shown in figure 6 uses the brake line pressure differential as a measure of the braking force differential. Depending on the sign of the difference, the aircraft is rolled in that direction where clockwise from behind is positive. If there is an error in heading the ailerons are used not to minimise the brake line pressure differential but rather to maintain a differential that will aid in returning the aircraft onto the centre line. This controller works with the assumption that the anti-skid system maintains an optimal level of braking, and that the brake line pressure on the port and starboard gears supply an equal brake force.

Aileron Augmented Friction Force Differential Control

There are three situations that will be described. One involves a normal landing with a steady head wind but with a variable friction coefficient on the starboard gear. The second involves an identical friction coefficient for both main gears but with a crosswind. The third scenario describes the combination of both a friction coefficient differential with cross winds. All three cases are described with the effects that occur when the nose gear is in the air and on the ground.

Variation in Friction Coefficient with Head Winds

The Simulation model of a large aircraft is brought to land. Once the main gears are on the ground the aircraft is subjected to a friction coefficient differential between the port and starboard gears. The port side is given a lower friction coefficient value than that of the starboard side. In order to maintain a high level of braking whilst keeping the aircraft heading aligned with the runway heading one of the following need to happen.

Solution 1: Simple. Main gear braking is reduced on both gears to the maximum braking force that can be maintained by the port gear. This increases the length of the landing run quite substantially and increases the time to reduce the speed to a safe taxi speed.

Solution 2: Current. Optimum main gear braking is maintained, though the friction force differential gives the aircraft a yawing moment that is countered by the rudder and the nose gear when it is on the ground. The size of the main gears braking force differential is limited by the yawing moment that the rudder can produce when the nose gear is in the air and the size of the yawing moment that the rudder and nose gear can produce when the nose is on the ground. Some aircraft also have differential reverse thrust, which can aid in this situation.

Solution 3: Proposed. Optimum main gear braking is maintained, though the friction force differential is minimised by rolling the aircraft with the ailerons onto the port gear (the gear that is most likely to skid). The Ailerons are deflected to increase the normal loading on the port side gear. This increase in the normal loading on the gear induced to counter the effect caused by the decrease in the friction coefficient gives a better friction force then if the gear was braking at the best friction force once the decrease in friction coefficient occurs. For various maximum friction coefficient values on the starboard side the minimum friction coefficient required on the portside is found based on the available normal loading differential on the main gears produced by rolling the aircraft with the ailerons. Figures 1, 2, 3 and 4 show the corresponding maximum available and minimum required friction coefficient values for different wind speeds with the nose in the air and on the ground. Looking at figure 1. During a velocity of 165 knots, if there is a friction coefficient of 0.5 on the starboard side then, the ailerons have the ability to roll the aircraft so that even if the port side gear can only achieve a friction coefficient of 0.05 the brake force differential can still be balanced. As the wind speed drops so does the allowable maximum difference in the port and starboard gear friction coefficient. Looking at the case with a 50 knot wind speed, at a friction coefficient value of 0.5 on the starboard side the minimum friction coefficient that is needed on the port gear is 0.45. Both these examples represent the three point aerodynamic braking scenario. The same can be achieved during the two point aerodynamic braking case. Figures 2 to 4 show the respective data for 4, 8, and 14 degrees of pitch. As the pitch angle increases the normal loading on the undercarriage decreases. This has the effect of giving a larger percentage change in the normal loading for an aileron deflection and so a larger difference in the allowable friction coefficients. The size of the brake force differential that can be minimised depends on the rolling moment that the ailerons can produce. This minimises any yawing moment produced by the friction force differential. The rudder and nose wheel steering can still be used to balance any yawing moment that the ailerons are unable to deal with alone.

Crosswinds

The Simulation model is brought to land on a runway with a constant friction coefficient. Once the main gears are on the ground the aircraft is subjected to a crosswind coming from the port side. This has the effect of increasing the lift produced by the port wing. The port gear has a lower normal loading. This results in a lower attainable maximum friction force by the port gear. The pilot has to keep the port wing down. The crosswind gives a positive side-force which causes the aircraft to move across the runway in the direction of a ground sideslip angle as shown in figure 5. In order to maintain braking whilst keeping the aircraft heading aligned with the runway heading one of the following need to happen.

Solution 1: Simple. Main gear braking is reduced on both gears to the maximum braking force that can be attained by the port gear. As in the case with head winds, this increases the length of the landing run quite substantially and increases the time to decelerate the aircraft to a safe taxi speed.

Solution 2: Current. Optimum main gear braking is maintained, though the friction force differential adds a second yawing moment to have to deal with. The rudder is already being used to keep the aircraft aligned with the runway heading. The ailerons are still being used to keep the port wing down though they are still unregulated. When the nose gear comes into contact with the runway surface it will provide additional support for yaw control. The anti-skid system can maintain an optimum level of braking from the point of view of the tires.

Solution 3: Proposed. Optimum main gear braking is maintained. The ailerons are used to minimise the friction force differential, which also solves the problem of keeping the wing down. The controller takes into account the brake line pressure. This is a function of the brake force that can be produced at the wheel, which in turn is a function of the normal loading on the strut. The problem no longer involves the friction coefficient but rather the normal loading. The effect is the same and the measured inputs are the same and the control action is the same and the controller is the same. The rudder and the nose gear, when it is on the ground, are used to counter any yawing moments so as to hold the aircraft heading in line with the runway.

Crosswinds with a Variation in the Friction Coefficient

This can be broken down into two scenarios.

- Port side crosswind with a port side drop in friction coefficient.
- Port side crosswind with a starboard side drop in friction coefficient.

Scenario 1
In the first case the port side crosswind has the effect of causing the aircraft to yaw negative or into the wind as in the pure crosswind problem. The moments produced by the vertical fin and the port side wing aerodynamic drag give the aircraft a negative yawing moment. The drop in the friction coefficient on the port gear gives a positive yawing moment. The crosswind gives a positive side force, which causes the aircraft to move across the runway in the direction of a ground sideslip angle as shown in figure 5. In this situation the drop in the brake force on the port gear is due to the combined effect the wind and the drop in friction coefficient have. The drop in the brake force on the port gear will inevitably be greater than any other case.

Solution 1: Simple. The starboard gear brake force is reduced so that it matches the port gear. This balances the yawing moment produced by the main gears. The rudder and nose gear, when it is on the ground, are used to yaw the aircraft slightly to the left of the runway heading. This reduces the wind sideslip angle which in effect reduces the side force caused by the crosswind, and at the same time increases the ground sideslip angle so that the undercarriage produces a sufficient side force to counter the remaining side force produced by the crosswind. Figure 5 is a schematic of the sideslip angles and heading. The ailerons are used to keep the port wing down though they are not regulated. The aircraft maintains the required heading but brakes far from optimally.

Solution 2: Current. Maintaining the maximum available brake force on both gears whilst keeping everything else the same as solution 1 has a higher brake force and reduces the landing run but is limited by the available yawing moment the rudder and the nose gear can produce.

Solution 3: Proposed. Exactly like solution 2 except that here the ailerons are used not just to keep the port wing down but to minimise the brake force differential and if possible to give a higher brake force on the port gear. The side force that is produced due to the crosswind can be dealt with by offsetting the balance on the brake line pressures to favour the port gear more than the starboard gear. This helps the rudder to maintain the aircraft heading to give a ground sideslip angle suitably large so that the undercarriage can provide a side force to counter the force induced by the crosswind. This takes the load off of the nose gear and the rudder.

Scenario 2

In the second case the port side crosswind has the effect of causing the aircraft to yaw negative or into the wind as in the pure crosswind problem. The port side wind also has the effect of reducing the normal loading on the port gear thus reducing the friction force. The moments produced by the rudder and the port side wing aerodynamic drag give the aircraft a negative yawing moment. The drop in the friction coefficient on the starboard gear also gives a negative yawing moment. The crosswind gives a positive side-force which causes the aircraft to move across the runway in the direction of a ground sideslip angle. For this scenario braking is reduced significantly on both the port and starboard gears.

Solution 1: Simple. The port gear brake force is reduced so that it matches the starboard gear. This balances the yawing moment produced by the main gears. The rest is the same as in scenario 1, solution 1. The aircraft maintains the required heading but does not brake optimally.

Solution 2: Current. Maintaining the maximum available brake force on the port gear whilst keeping everything else the same as in solution 1 has a higher brake force and reduces the landing run. The rudder and the nose gear in this case will be used to counter the yawing moment that is produced by the differential brake force especially if there is a large moment. Again this is limited by the available yawing moment the rudder and the nose gear can produce.

Solution 3: Proposed. This is exactly like solution 2 except that here the ailerons are used not just to keep the port wing down but to minimise the brake force differential and to give a controlled brake force advantage to the port gear. This does not load the nose gear and the rudder with as high a yawing moment to deal with. The ailerons are used in this case to minimise the losses. The aileron controller works with a brake line pressure differential rather than an absolute brake line pressure value. There is a drop in the brake line pressure on both port and starboard gears for this case. The controller is not affected by this and will provide an aileron deflection in favour of the gear with the lesser brake line pressure. The side force that is produced due to the crosswind can be dealt with by offsetting the balance on the brake line pressures to favour the port gear more than the starboard gear. This helps the rudder to maintain the appropriate heading.

Optimising Two Point Aerodynamic Braking.

Taking a step back to two point aerodynamic braking. Assuming that the friction force differential problem is solved with the use of the aileron augmented friction force differential controller, main wheel braking can be introduced before the nose gear touches the ground and after the wheel speeds match the ground speed. The aircraft is then held or rotated down at an optimum pitch angle depending on the available pitching moment. If the nose is held up for too long then the aircraft will rotate too quickly once the available pitching moment is no longer sufficient, resulting in the nose coming down hard. Figure 7 shows the elevator/brake-coupling controller used to optimise the aircraft pitch angle during two point aerodynamic braking. The inputs for the elevator controller are available pitch angle, available elevator deflection, Slip Ratio Differential and pitch rate and limit. The outputs are controller elevator deflection. The inputs for the anti-skid component are elevator deflection and limit and slip ratio differential. The outputs are brake pressure. The aircraft is brought down onto the main gears. The wheels spin up. Based on the available elevator deflection and slip ratio differential a certain amount of braking is initiated using the elevators to maintain the optimum pitch angle and pitch rate.

Discussion

The first controller design is a new concept, which is in need of extensive practical examination. The research completed so far has been on a p.c. based simulation model and there is still a lot of work to be done. There is no real flying time for this controller.

The simulation test bed, as detailed as it is, can not be a substitute for the real thing. The first controller proposed depends highly on the accuracy of the sub systems.

As mentioned before, it is assumed that the brake line pressures on the port and starboard gears will produce a proportional brake force. If a certain brake line pressure does not produce an equivalent brake force on both main gears this can be solved by giving either port or starboard sides a false zero or a larger gain depending on the problem.

It is believed that in the case of runway height variation that a problem may arise. If a runway has a variation in height that is not mirrored on both gears then the controller may have a tendency to attenuate any rolling oscillation induced by such a variation.

Conclusions

The proposed solutions for the first controller have one thing in common. They all introduce the use of a controlled aileron deflection not just to keep the wing on the wind side down but as a means of controlling the braking difference between the port and starboard sides. The rationale behind the controllers has been presented for different scenarios allowing for variation in friction coefficient, for crosswinds and a combination of the two.

Based on the theoretical test cases and manually executed manoeuvres on a non-linear simulation model the friction coefficient differential limits for various speeds have been presented as starting evidence that the use of ailerons has the effectiveness to provide a sufficient return from a large friction coefficient differential. The initial structure of the controllers given shows the expected control inputs and outputs.

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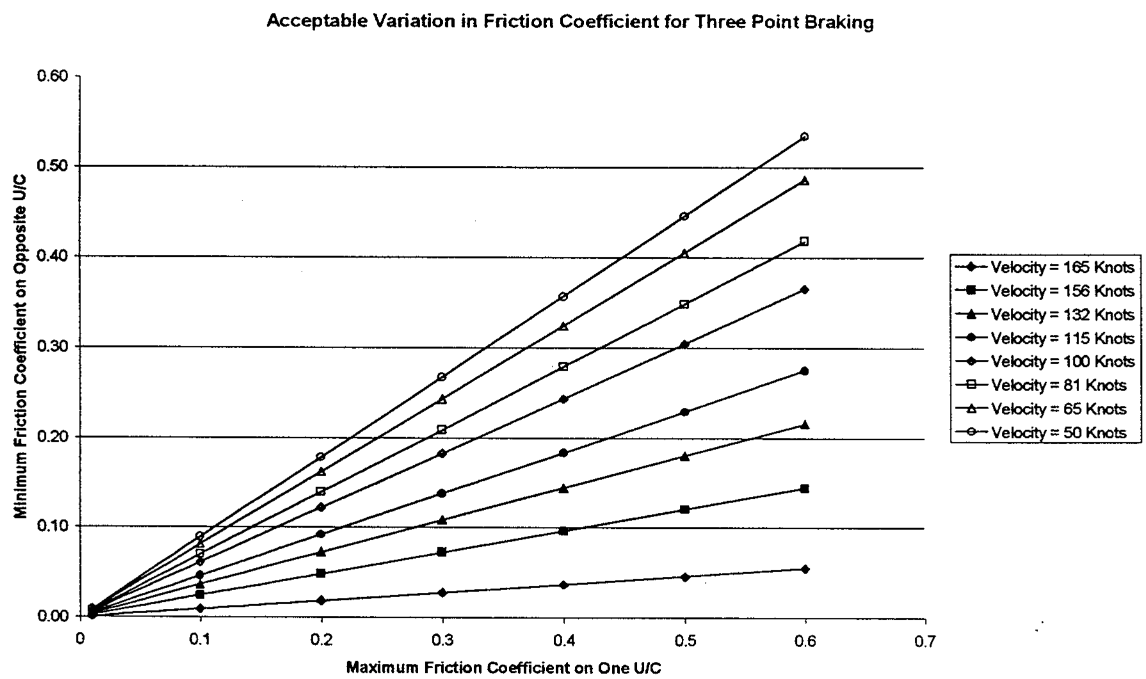


Figure 1: Acceptable variation in friction coefficient for three point braking.

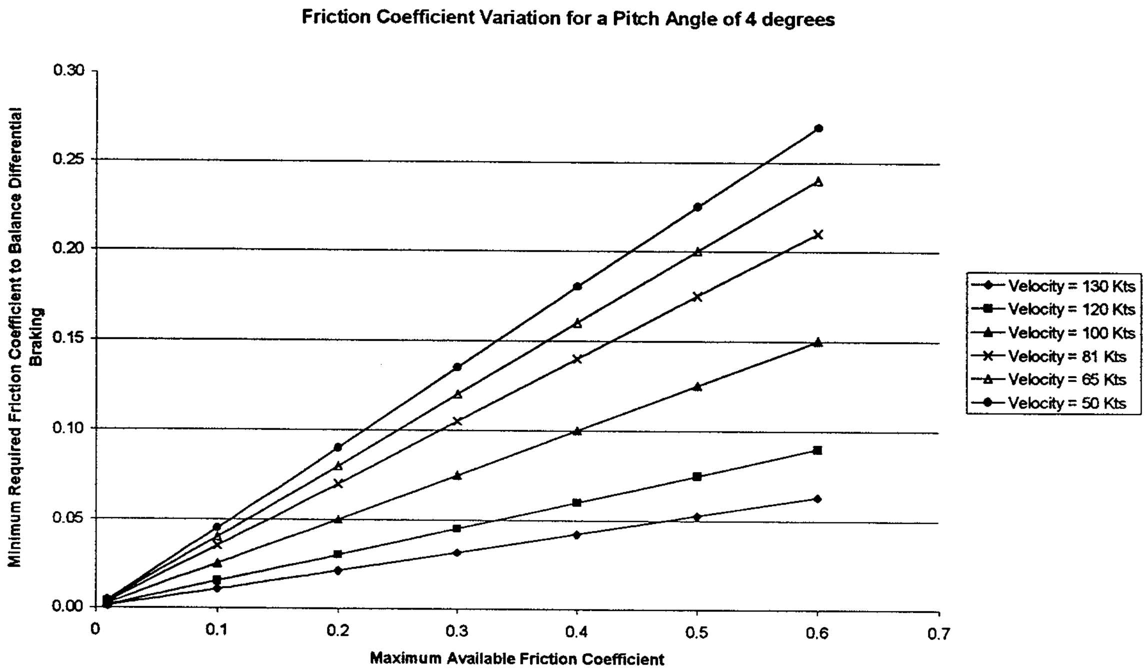


Figure 2: Friction coefficient variation for a 4 degree pitch angle.

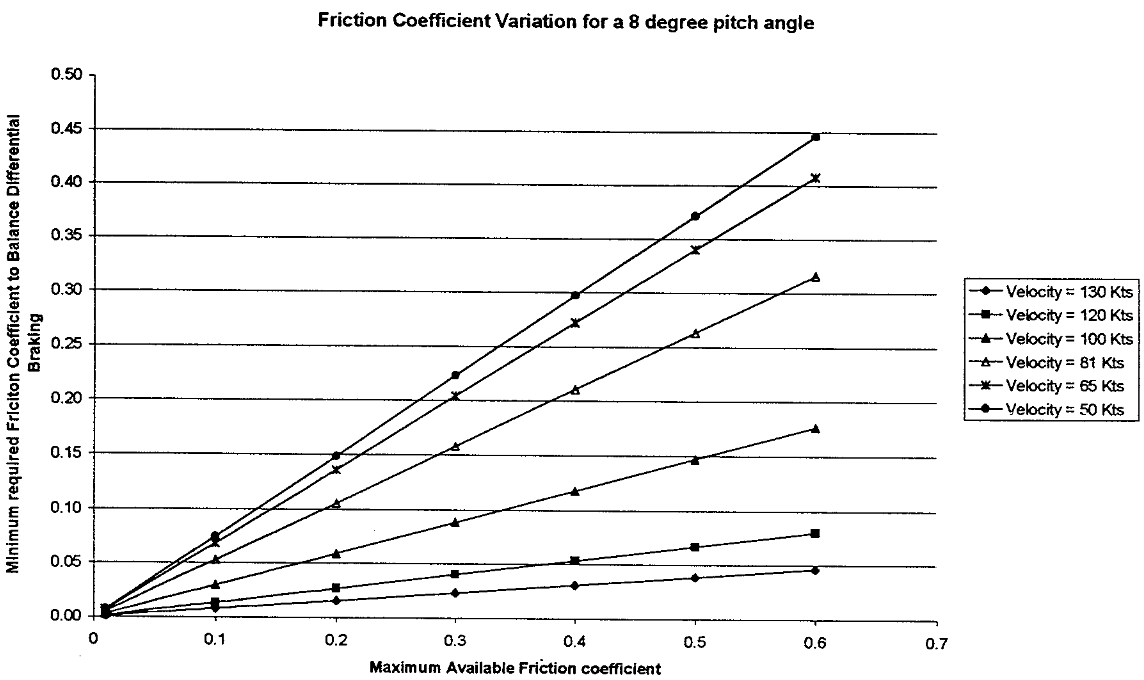


Figure 3: Friction Coefficient Variation for an 8 degree pitch angle.

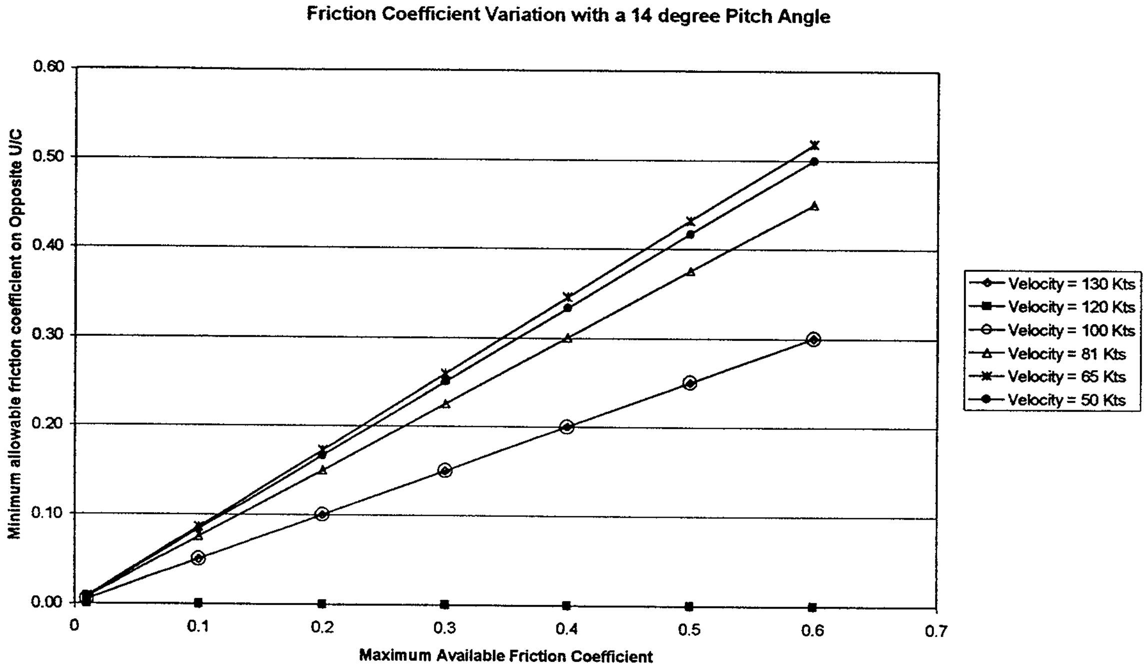


Figure 4: Friction coefficient variation with a 14 degree pitch angle.

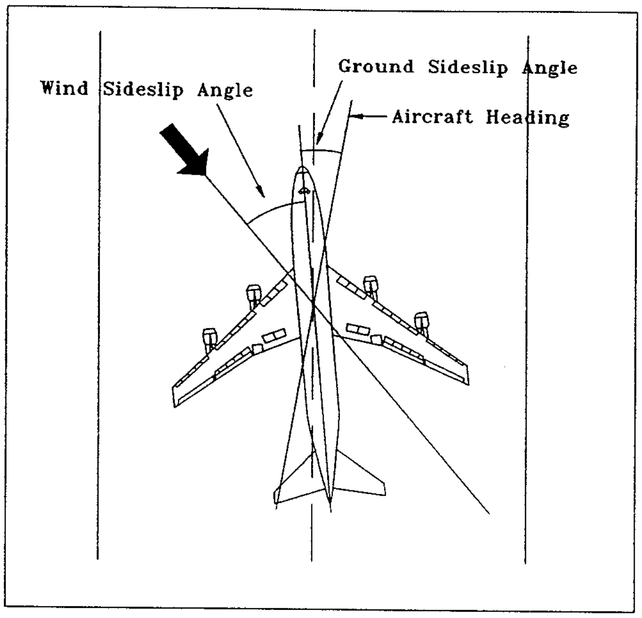
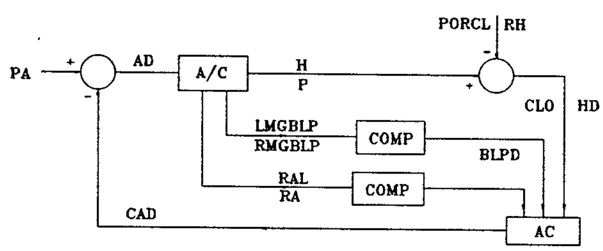


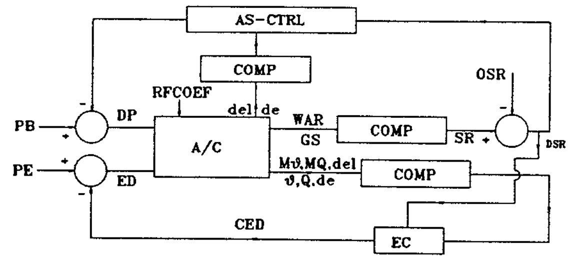
Figure 5: Relation of Ground and Wind Sideslip Angles with Heading.



Note: RAL approaches Zero as the Aircraft enters ground proximity and nears touchdown
BLPD is set to Zero when in the air

COMP = COMPARATOR
PA = PILOT AILERON
AD = AILERON DEMAND
A/C = AIRCRAFT
CAD = CONTROLLER AILERON DEFLECTION
LMGBLP = LEFT MAIN GEAR BRAKE LINE PRESSURE
RMGBLP = RIGHT MAIN GEAR BRAKE LINE PRESSURE
H = HEADING
P = POSITION
RAL = ROLL ANGLE LIMITS
RA = ROLL ANGLE
BLPD = BRAKE LINE PRESSURE DIFFERENTIAL
RH = RUNWAY HEADING
PORCL = POSITION OF RUNWAY CENTRE LINE
CLO = CENTRE LINE OFFSET
HD = HEADING DEVIATION
AC = AILERON CONTROLLER

Figure 6: Aileron control system block for Air and Ground Ailerons.



note: Mϑ decreases as wind speed decreases. This is to ensure that the nose is brought down slowly.
DSR ideally should be ≤ zero. If it is greater than zero then it should be kept as close to zero as possible.

Aileron/Brake Coupling Controller.

DP = DEMAND PRESSURE
WAR = WHEEL ANGULAR RATE
COMP = COMPARATOR
GS = GROUND SPEED
SR = SLIP RATIO
OSR = OPTIMAL SLIP RATIO
AS-CTRL = ANTI-SKID CONTROLLER
PB = PILOT BRAKING
RFCOEF = RUNWAY FRICTION COEFFICIENT
PE = PILOT ELEVATOR
ED = ELEVATOR DEMAND
EC = ELEVATOR CONTROLLER
A/C = AIRCRAFT
CED = CONTROLLER ELEVATOR DEFLECTION
Q = PITCH RATE
de = ELEVATOR DEFLECTION
del = ELEVATOR DEFLECTION LIMITS
ϑ = PITCH ANGLE
MQ = MAXIMUM ALLOWABLE PITCH RATE
Mϑ = MAXIMUM ALLOWABLE PITCH ANGLE
DSR = DIFFERENCE IN SLIP RATIOS

Figure 7: Elevator/Brake Controller Coupling to optimise Two Point Aerodynamic Braking.