Anti-Skid Aircraft Braking Mechanism using Consensus Control over Wireless Avionic Intra-Communication

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Abstract

This article discusses the anti-skid braking control mechanism of an aircraft. A proportional-integral (PI) controller is used by wheels to generate the desired braking torque to stop the aircraft while landing. Potential runway variations are considered, which will affect the friction force available to each wheel. Variations in wheel forces generate drag torque, causing the aircraft to drift away from the runway. As a result, a supervisory consensus controller has been introduced, which will adjust the braking torque of each wheel to achieve equal force on each wheel. Losses due to the wireless communication channel affect the performance of the consensus controller; therefore, packet losses have been studied. The proposed model is tested and simulated to find out how well the consensus controller works over a noisy channel.
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Index Terms—Anti-skid, Consensus control, Runway variations, Drag torque on aircraft, PI Control, Packet loss, Noisy channel.

I. INTRODUCTION

Currently, the next generation of commercial aircraft is being developed to provide more reliable, cost-efficient, and safer flights. Part of this effort is the introduction of the wireless avionics intra-communications (WAIC) system [1]. This system aims at reducing aircraft weight by replacing wired with wireless systems, as cabling and wiring present a significant cost associated with the fabrication, maintenance, and weight of an aircraft. A particular advantage of a wireless system is the operational enhancement of landing gear sensors (wheel speed for anti-skid control and position feedback for steering), as it provides increased flexibility for monitoring moving and rotating parts. These landing gear functions send important status information in real-time to keep the flight’s high levels of reliability and safety.

In this context, a landing gear control system operating over a wireless sensor network must be at least as reliable as one operating over a traditional wired network. However, the wireless environment imposes a different challenge for connection reliability where communication is performed in a shared medium (over the air) causing radio interference from other systems (e.g., radio-altimeters, other WAIC networks), which can cause packet losses and transmission delays. Therefore, wireless communication protocols need to be considered that mitigate those effects, while at the same time, the design of the landing gear control systems needs to consider the limitations of such communication protocols.

Another important factor for enhancing the cost-efficiency of a flight is shortening the landing distance. The challenge here is the deceleration, where various forces (e.g., air resistance, reverse thrust) are used to stop the aircraft, including the landing wheel braking force, which, if applied too hard, may cause the aircraft to skid and cause an accident [2]. This braking force is heavily dependent on runway friction, which changes dramatically with even minor changes in the weather, such as a few drops of rain or snow [3]. As a result, an anti-skid brake control mechanism is used to maximize the available braking resources. The maximum force that can be applied to the wheel without skidding is determined in the anti-skid brake control model by using the friction of the runway surface [4].

A slip ratio can be used to regulate the friction coefficient. A local proportional-integral (PI) controller is used to control the slip ratio to a desired value [5]. Because the friction force available changes due to changes in runway conditions, the braking force applied to the main landing gear may differ for different wheels. Uneven forces applied to different wheels cause a drag force on aircraft while landing [6].

To avoid this disruption, we propose a supervisory consensus control mechanism in which the friction coefficient provided to each wheel in the main landing gear must be equal. In this consensus control mechanism, all the wheels will communicate with their connected neighbours to exchange information about the friction exerted on each wheel and adjust their desired slip ratio so that all the wheels have the same force on each wheel to keep the aircraft following the path of the runway in the presence of uncertain changes in runway conditions.

To develop consensus control, all wheels need to transmit information to a centralized consensus controller. Then the consensus controller estimates the friction force based on the received information and communicates it back to the wheels. While most of the existing literature on consensus control assumes perfect communication, in most of the recent developments using wireless systems, communication noise and uncertainties can degrade the performance of the consensus controller. In this paper, we analyze the effect of the wireless...
system and propose a simple communication protocol that helps mitigate the interference uncertainty and coordinates sensor data transmissions between the different wheels. We also propose an estimation tool to mitigate the effects of losing information due to packet loss. Following on from this, we investigate the impact of communication disruptions over the wireless channel on the overall supervisory control performance. The following are the main contributions to this paper:

- Propose a consensus control algorithm to estimate the longitudinal forces on each wheel, using a basic anti-skid model and a PI controller to generate the braking torque as a function of the slip ratio. Then updating the operating slip ratio by changing the desired slip ratio with the help of consensus control, to keep the aircraft on a straight path on the runway.
- Propose the use of a wireless communication protocol for centralized consensus control, using a carrier-sensing mechanism to avoid interference, time-slot scheduling to coordinate the transmissions, and the estimation of missing information.
- Investigate the impact of communication uncertainties on consensus control.

The remainder of this paper is organized as follows: We list and discuss related work in section II. The anti-skid brake control model is discussed in section III. In section IV, the supervisory consensus control model is presented. Our wireless communication channel model is developed in section V. We present and discuss simulation results in section VI and conclude with section VII.

II. RELATED WORK

The operation of aircraft landing gear is reviewed in [7], [8], where the articles survey and highlight the different problems of vibration and oscillations in aircraft due to braking. Anti-skid control landing gear of an aircraft is discussed in [4], where the authors have validated the anti-skid model with some experimental results. A mixed slip and sliding mode control-based anti-skid model is discussed in [9], in which the authors use sliding mode observer-based control to estimate the speed of the aircraft. The relation between anti-skid controller parameters and braking actuators is discussed in [10], in which the controller set-point is analyzed with respect to the total lifespan of wear dynamics. A fuzzy logic-based anti-skid model is designed to suppress the effect of faults and disturbances in the controller while braking in [11]. An extended stiffness-based runway maximum friction method is proposed in [12] to determine the maximum friction available. The aircraft will operate at the maximum available friction on the wheel.

The current literature has discussed the anti-skid model of the aircraft, but none of the work takes into account the sudden change in runway conditions. In reality, the friction force changes with runway conditions. Therefore, there is a need for a certain level of consensus among the wheels of the main landing gear so that, if the surface conditions change, the consensus controller will automatically adjust the slip ratio for each wheel so that all wheels have the same forces acting on them. Consensus control of multi-agent systems has been introduced in [13], where different consensus constraints and typologies of multi-agent systems are discussed. Average consensus algorithms are discussed in [14]–[17], where all agents connected to a system will reach a common value, which is the average of their initial state values. On the other hand, a leader-follower-based consensus control mechanism is discussed in [18]–[21], where one of the agents acts as a leader, which will dictate the value that all the followers have to reach.

However, the preceding literature on consensus control has not accounted for communication uncertainties. Perfect communication has been assumed between the agents with no communication delays or uncertainties [13]–[21]. Recently, some works considered wireless channel communication uncertainties. In [22], the authors discuss consensus control with random packet loss and delays and calculated the upper bound on the delays. Simple non-identical packet loss is discussed in [23], whereas random packet loss for an event-based consensus controller was introduced in [21]. In [24], the authors discussed communication delays for a consensus controller as a denial of service attack, where the attack can be seen as a communication loss. A time-varying delay-based consensus control scheme is discussed in [25]. In the prior literature, authors have studied the impact of random losses and delay on the system, but they have not discussed the effect of wireless communication protocol design and the radio interference intensity in the context of a wireless avionics environment. Actual packet losses in wireless avionics environments are different from those modelled or predicted by consensus control in the current literature. Previous works do not deal with packet loss, and as the proposed system is time-critical, retransmission is not a viable option in this particular case. Therefore, we propose an estimation-based solution to packet losses in this work.

III. MATHEMATICAL MODEL FOR ANTI-SKID BRAKE CONTROL

A. Friction Coefficient

We will begin our discussion by defining the slip ratio $\lambda_i$. It is the control input given to the local controller, which will generate the braking torque used by the wheel to stop the aircraft. It is defined as the ratio of the angular speed of the wheel to the velocity of the aircraft:

$$\lambda_i = \frac{v - \omega_i r}{v}$$

(1)

where $v$ is the velocity of the aircraft, $\omega_i$ is the angular speed of the $i^{th}$ wheel of the main landing gear of the aircraft, and $r$ is the radius of the wheel. This slip ratio, $\lambda_i$, has a value $\lambda_i \in (0, 1]$, where 1 means the wheel is fully locked [26].

Next, we need to define the lateral friction coefficient $\mu_i$, which is the non-linear function of slip ratio $\lambda_i$, where $\mu_i$ can be defined as [26]...
\[ \mu_i(\lambda_i) = \alpha_i (1 - \exp^{-\lambda_i \beta_i}) - \gamma_i \lambda_i \]  

(2)

where \( \alpha_i, \beta_i, \gamma_i \) are the parameters dependent on the runway conditions and are given in Table I.

### TABLE I

VALUES OF PARAMETER \( \alpha_i, \beta_i, \gamma_i \) UNDER DIFFERENT RUNWAY CONDITIONS [26]

<table>
<thead>
<tr>
<th>Runway condition</th>
<th>( \alpha_i )</th>
<th>( \beta_i )</th>
<th>( \gamma_i )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dry</td>
<td>1.28</td>
<td>23.99</td>
<td>0.52</td>
</tr>
<tr>
<td>Wet</td>
<td>0.86</td>
<td>33.82</td>
<td>0.35</td>
</tr>
<tr>
<td>Snow</td>
<td>0.19</td>
<td>94.13</td>
<td>0.06</td>
</tr>
</tbody>
</table>

The function of the friction coefficient in terms of slip ratio is plotted in Fig. 1. The slip ratio controls the amount of friction available to the wheel. It can also be noted that the maximum friction available to the wheel is available at similar \( \lambda \) values regardless of the runway conditions.

![Friction Coefficient vs Slip Ratio](image)

**Fig. 1.** \( \mu - \lambda \) curve under different runway conditions.

### B. Wheel Dynamics

In this section, we will define the wheel dynamics of the aircraft with the help of Newton’s laws of mechanics [27]. The laws state that the sum of all the forces acting on the aircraft is equal to the acceleration times the mass of the aircraft. The wheel dynamics and the forces acting on the wheel are shown in Fig. 2.

\[ M_a \frac{dv}{dt} = -F_x \]

(4)

where \( F_x = \mu(\lambda)F_N \) and \( F_N = M_ag/n \) is the normalised force acting on the wheel of the aircraft. \( M_a \) is the mass of the aircraft, \( g \) is the gravitational constant, and \( n \) is the number of wheels on the main landing gear.

The law of conservation of angular momentum around the wheel yields

\[ J_w \frac{d\omega}{dt} = rF_x + T_b \]

(5)

where \( J_w \) is the moment of inertia of the wheel and \( T_b \) is the braking torque applied by the local controller to the wheel. We will design the controller for \( T_b \) in the next subsection.

The two equations of motion become

\[ M_a \ddot{v} = -F_N \mu(\lambda) \]

(6)

\[ J_w \ddot{\omega} = rF_N \mu(\lambda) + T_b \]

(7)

![Wheel dynamic model while braking](image)

**Fig. 2.** Wheel dynamic model while braking

### C. Aircraft Dynamics

During landing, when the aircraft touches the ground, the plane experiences torque due to different forces acting on the main landing gear. The torque will impact the momentum over the plane and is defined as

\[ J_a \ddot{\omega}_a = T_a \]

(8)

where \( J_a \) is the moment of inertia of the plane and \( \ddot{\omega}_a \) is the angular acceleration of the plane. \( T_a \) is the torque acting on the plane while landing and is defined as

\[ T_a = F_l l_l - F_r l_r \]

(9)

where \( F_l, F_r \) are the forces acting on the left and right landing gears, respectively, and \( l_l, l_r \) are the distances of the landing gears from the central axis of the plane. Ideally, to keep the plane in a straight direction and follow the central axis of the plane, \( T_a \) needs to be zero.
D. Braking Torque Controller Design

To stop the aircraft, the braking torque is applied to exert force on the wheels with the help of friction. We set a desired slip ratio $\lambda_d$ by which we can adjust the friction available to the wheel from the runway. We then measure the wheel speed and calculate the current slip ratio $\lambda_i$. To get the wheel to a speed that is close to the desired slip ratio, we use simple Proportional-Integral (PI) control that will control the slip ratio of the wheel. The output of the PI controller will be an error between the desired and actual slip ratio. This error will generate the braking torque as shown in Fig. 4.

\[ e = \lambda_d - \lambda_i \]  
\[ \dot{T}_b = K_p e + K_i \int e \, dt \]  (11)

where $K_p$, $K_i$ are proportional and integral gains, respectively.

IV. SUPERVISORY CONSENSUS CONTROL

We have discussed the anti-skid brake control mechanism of an aircraft in section III. As one can see, the longitudinal force $F_x$ acting on the wheel is significant and dependent on $\mu_i$, which depends on the runway surface. Therefore, under a slight change in runway condition, the aircraft will not follow the runway tracking path and might slip off the runway, which may cause an accident. To avoid this consequence, we propose a supervisory control mechanism that will yield a consensus among the wheels so that all the wheels will experience the same longitudinal force, $F_x$ regardless of the runway condition. Therefore, in this section, we develop a consensus control mechanism in which the wheels on the left landing gear experience a different longitudinal force as compared to the right landing gear, but the consensus control mechanism will output a common value of $\mu_c$ such that every wheel has the same force, which leads to adjusting the desired slip ratio coefficient $\lambda_d$. For the wheel to develop a consensus among its neighbours, each wheel acts like an agent, and a connectivity matrix will define its connectivity with its neighbours. We will first define the connectivity matrix using algebraic graph theory.

A. Algebraic Graph Theory

We use an undirected Graph $G$ to represent the communication topology among the wheels. We define $G = \{V, E, A\}$ where $V = \{v_1, v_2, \ldots, v_n\}$ is the vertex set representing $N$ wheels. $E$ is the set representing the communication links between the wheels. $E_{ij}$ is the edge between two nodes (wheels) $(v_i, v_j)$, $i, j \in \{1, 2, 3, \ldots, N\}$, $i \neq j$. If $E_{ij} \in E$, $v_i$ is neighbour to $v_j$ then they can communicate with each other. The adjacency matrix is $A = [a_{ij}] \in R^{N \times N}$ with $a_{ij} = 1$ when $i$ is connected to $j$, or $a_{ij} = 0$ otherwise. The in-degree matrix is a diagonal matrix with $S = diag\{s_1, s_2, \ldots, s_N\}$ with $s_i = \sum_{j=1}^N a_{ij}$ where $N_i$ is the number of control agents (wheels) connected to the $i^{th}$ control agent. The graph Laplacian matrix is $L = S - A$, where all row members add up to zero. $L$ is a symmetric positive semi-definite matrix. The convergence rate (time for $F_x$ consensus) will depend on the eigenvalues of $L$ and is given by the second smallest eigenvalue of $L$. Let $L = [l_{ij}]_{N \times N}$ where $l_{ij} = l_{ii}$ on-diagonal, and $l_{ii} = \sum_{i \neq j} a_{ij}$ whereas $l_{ij}$ off-diagonal is $l_{ij} = -a_{ij}$.

B. Consensus of Longitudinal Force

Assume we have wheels with longitudinal forces $\{F_{x1}, F_{x2}, F_{x3}, \ldots, F_{xn}\}$ trying to reach consensus. Each wheel is driven by its own local controller and has its own control input. Let $u_i(t)$ be the control input. This input is defined as the sum of the differences of forces obtained from neighboring wheels to the $i^{th}$ wheel as defined in (13). This can be further represented with the Laplacian matrix $L$ as in (14). To achieve consensus, we create a feedback control law $u_i$ for each wheel that makes use of the information obtained over the communication network at sampling time $t_k$, $k = 0, 1, 2, \ldots$, and we suppose that for all initial conditions, $\lim_{t \to \infty} (F_{ix}(t) \to F_{ref}(t))$, $i \in \{1, N\}$ where $F_{ref}$ is the reference force. Also, we assume that between any two consecutive control updates, the input of each wheel is held constant in a zero-order hold fashion equal to the last control update.

\[ \dot{F}_{ix} = u_i(t) \]  (12)
where

$$u_i(t) = - \sum_{i,j \in N} (F_{ix} - F_{jx})$$  \hspace{1cm} (13)

or

$$u_i(t) = -LF_{ix}$$  \hspace{1cm} (14)

The consensus control mechanism is depicted in Fig. 5, where the local PI controller will generate the slip ratio $\lambda_i$. The slip ratio will generate friction $\mu_i$ which will exert force on the wheel. The force $F_x$ is given as an input to the consensus controller, and the consensus controller will generate a new $\mu_{ci}$ which will tell the system to operate at a certain desired slip ratio, $\lambda_{di}$, meaning, the desired slip ratio for each wheel is updated to keep the longitudinal forces acting on the wheels the same.

![Fig. 5. Supervisory Consensus Control](image)

V. WIRELESS COMMUNICATION MODEL

The communication to develop consensus among the wheel agents is carried out over the wireless channel by a gateway, which requests from each wheel the latest information about the wheel’s friction force $\mu_i$. Once the wheel has provided the friction force, the consensus controller estimates the friction force $\mu_{ci}$ which should act on each wheel and then communicates back the desired slip ratio $\lambda_{di}$ to the wheel as shown in Fig. 6. The wireless channel is a shared resource between different radio-altimeter and various other devices also occupy the channel. The channel occupancy depends on the packet arrival rate and transmission duration distributions.

The consensus controller gateway accesses the wireless channel to request the wheel’s friction state, and if the channel is free it will start the requested transmission, otherwise, it will back off. The frequency at which the gateway accesses the channel is the sampling time at which the consensus controller will update its input. A wheel that receives a request will send the data to the controller on its communication time slot over the channel. The controller will receive the friction information from all the wheels during each wheel’s time slot, and then develop a consensus and formulate the estimated friction that each wheel should experience. Based on the estimated force, a desired slip ratio $\lambda_{di}$ is computed and broadcast to each of the wheels in the next communication slot, as shown in Fig. 6.

![Fig. 6. Wireless communication protocol](image)

A. Communication Error Model

Due to the shared wireless channel resources, packets received at both the consensus gateway (friction data) and over the sensors at each wheel (gateway request and/or consensus output) might contain errors due to interference. When the gateway request for data from the wheel is lost, the wheel sensor will not be triggered to transmit the latest friction information. Similarly, even if the request is successfully received and the sensor sends the friction data, that data might be lost due to interference or noise, therefore the gateway has to be able to estimate the data it was expecting from the sensor. On the sensor side, when the consensus controller outputs the desired slip ratio and transmits it to each sensor, that packet might also be lost, and the sensor also has to estimate the control information. We can also use machine learning-based estimation methods like reinforcement learning to estimate $\mu_{est}$, but these estimations are not in the scope of this paper. Therefore, we use a statistical abstraction of the estimation process by modelling this estimation at the gateway and sensor sides as $\mu_{est} = \mu_{real} + \epsilon$, where $\epsilon$ is a normal distribution with a zero mean and $\sigma$ the standard deviation, which will represent the estimation accuracy.

VI. NUMERICAL RESULTS

A. Simulation Setup

We have validated our proposed model with an example of 4 wheels on the main landing gear, two on the left side and two on the right side of the aircraft. We use the simple PI controller for anti-skid brake torque control and add our supervisory consensus control. The parameters used in the model are taken from [6] and are given in Table II.

B. Consensus with Perfect Communication

We will first simulate the model without using the consensus controller and observe the impact on the aircraft of different friction forces acting on each wheel. In Fig. 7, we can see that
### Table II
**Parameters of an aircraft [6]**

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$M_a$</td>
<td>Aircraft mass</td>
<td>17256 kg</td>
</tr>
<tr>
<td>$g$</td>
<td>Gravitational constant</td>
<td>9.81 m/sec$^2$</td>
</tr>
<tr>
<td>$r$</td>
<td>Radius of the wheel</td>
<td>0.4 m</td>
</tr>
<tr>
<td>$J_w$</td>
<td>Rotational inertia of the wheel</td>
<td>1.885 kgm$^2$</td>
</tr>
<tr>
<td>$J_a$</td>
<td>Inertia of aircraft</td>
<td>6141855 kgm$^2$</td>
</tr>
<tr>
<td>$l_l$</td>
<td>Distance of left gear from axle</td>
<td>10 m</td>
</tr>
<tr>
<td>$l_r$</td>
<td>Distance of right gear from axle</td>
<td>10 m</td>
</tr>
<tr>
<td>$v_0$</td>
<td>Initial velocity of aircraft</td>
<td>72 m/s</td>
</tr>
<tr>
<td>$dt$</td>
<td>Sampling time</td>
<td>5 ms</td>
</tr>
<tr>
<td>$st$</td>
<td>Slot time</td>
<td>144 µs</td>
</tr>
</tbody>
</table>

The friction forces acting on wheels $w_1$, $w_2$ are different from those on wheels $w_3$, $w_4$. This difference in forces is due to the fact that the left landing gear ($w_1$, $w_2$) is on the wet side and the right landing gear ($w_3$, $w_4$) is on the dry side of the runway. This difference in friction force will cause a mismatch in the velocity of the wheels, as shown in Fig. 8. The larger friction force acting on the right landing gear ($w_3$, $w_4$) will generate a high drag torque $T_a$ force on the aircraft, and the aircraft will tend to move away from the runway path. The drag torque acting on the aircraft is shown in Fig. 9.

To have a safe and smooth landing, we need to minimise the drag force $T_a$ acting on the aircraft. For this, we want the friction force acting on all the wheels to be equal. For that, we use our supervisory consensus controller, which will receive the actual friction forces acting on the wheels and generate an estimate of the equal amount of forces that should act on each wheel. To generate those equal forces, we need to adjust our desired slip ratio $\lambda_d$. Therefore, the consensus controller will output the estimated friction coefficient $\mu_{ci}$ for each wheel, as well as the desired estimated slip ratio $\lambda_d$.

We simulate our model in the presence of a supervisory consensus controller to study the effect on the aircraft’s drag force. In Fig. 10, we can see the estimated $\mu_{ci}$ which the consensus controller will output. It is clear from the figure that the forces exerted on all wheels are approximately the same. The velocities of the wheels are also shown in Fig. 11. We can see that the velocities of each wheel are also the same. Finally, the drag force on the aircraft is shown in Fig. 12. It is clear from the results that the drag force acting on the aircraft is significantly lower with consensus control as compared to without consensus control.

### C. Consensus with Communication losses

Following consensus control with perfect communication, we now examine the effects of transmission delays and packet loss due to interference in terms of landing distance. We initially chose a sampling time of 5 ms. When transmission losses increase, as shown in Fig. 13, the landing distance is significantly increased, even beyond a safe distance, when we are not estimating the slip ratio received from the neighbour.
wheels. In order to counteract the effects of packet loss, we propose to estimate the lost values using a Normal distribution with zero mean. We tested different standard deviations \( \sigma \) and found that the best-fit estimation is with \( \mathcal{N}(0,0.02) \). This achieves an acceptable level of performance even though there were 25% communication losses (see Fig. 13).

We then looked at the performance of consensus control in terms of landing distance with varying the sampling time while keeping the losses constant (5%), as shown in Fig. 14. From the result, it is evident that the communication time interval (which is equal to the sampling time) has also a significant effect on the system performance. To achieve an acceptable landing distance, the sampling time will have to be chosen between 5\( ms \) – 10\( ms \), depending on the interference losses.

We have also looked at the maximum drag torque an aircraft experiences under wireless communication constraints. In Fig. 15 we can see that, while keeping the sampling time of 5\( ms \) the same for all simulations, the maximum drag an aircraft experiences without consensus is very high but should ideally be zero. While consensus control results in much lower drag despite communication impairments, the drag torque is still not close to zero. However, the proposed estimation approach, with \( \mathcal{N}(0,0.02) \), overcomes the impairments and results in similar control performance as perfect communication.

**VII. CONCLUSION**

In this article, we studied a PI controller-based anti-skid braking control mechanism to control the braking torque on the main landing gear of an aircraft. We have investigated the effects of variations in runway conditions on the friction force at each wheel. Different forces experienced at each wheel lead to drag on the aircraft, which can result in an aircraft drifting off the runway during landing or result in a much longer landing distance. We propose a supervisory consensus
control to adjust the desired slip ratio at each landing gear wheel to eliminate the effects of runway conditions. In our implementation, the consensus controller exchanges information over a wireless avionic intra-communication (WAIC) channel, which can result in packet losses and transmission delays. As part of our consensus controller design, we propose an estimation algorithm to compensate for communication losses. Our simulations demonstrate that the proposed consensus control approach can achieve a significantly reduced drag on the landing gear wheels and an acceptable landing distance range. The estimation approach makes the consensus controller robust against wireless communication impairments, allowing the use of wireless communications for aircraft control, leading to reduced cabling and aircraft weight.

REFERENCES


