Cockpit Automation Fact Sheet

Automation Bias and Surprise
Introduction

In aviation, modern aircraft have become increasingly reliant on cockpit automation to provide a safe and efficient flight. It has provided aircraft with increased passenger comfort, improved flight path control, reduced workload and many other advantages. However, due to cockpit automation problems concerning the human-computer interaction have risen that have led to fatal air accidents. Two main phenomena can be pointed out that cause these problems and influence aviation safety: automation bias and automation surprise. To solve these problems, two main solutions have been proposed: revise pilot training and redefine the role of the pilot in the cockpit. To introduce and substantiate this topic, two examples are given of flight accidents that have happened due to human-cockpit automation error: Turkish Airlines flight TK1951 on route from Istanbul Atatürk to Amsterdam Schiphol Airport in 2009 and Air France flight AF447 from Rio de Janeiro Galeão to Paris Charles de Gaulle also in 2009.

Turkish Airlines crashed during approach

A Boeing 737-800 (flight TK1951) operated by Turkish Airlines was flying from Istanbul Atatürk Airport in Turkey to Amsterdam Schiphol Airport, on 25 February 2009. During the approach to runway 18 Right (18R) at Schiphol Airport, the aircraft crashed into a field at a distance of about 1.5 kilometres from the threshold of the runway. This accident cost the lives of four crew members, including three pilots, and five passengers, with a further three crew members and 117 passengers sustaining injuries.

What caused the aircraft to crash?

The Boeing 737-800 can be flown either manually or automatically. This also applies to the management of the engines. The auto-throttle (managing throttle settings in order to maintain a certain speed) regulates the thrust of the engines. The aircraft is fitted with two radio altimeter systems, one on the left and one on the right. In principle, the auto-throttle uses the altitude measurements provided by the left radio altimeter system. Only if there is an error in the left system that is recognised as such by the system, the auto-throttle and various other aircraft systems use the right-hand radio altimeter.

The aircraft was being flown by the first officer, who was sitting on the right-hand side. His primary flight display showed the readings measured by the right radio altimeter system. During approach, the left radio altimeter system displayed an incorrect height of -8 feet. This could be seen on the captain’s (left-hand) primary flight display. The first officer’s (right-hand) primary flight display, by contrast, indicated the correct height, as provided by the right-hand system. The left-hand radio altimeter system, however categorised the erroneous altitude reading as a correct one, and did not record any error. This is why there was no transfer to the right-hand altimeter system. In turn, this meant that it was the erroneous altitude reading that was used by various aircraft systems, including the auto-throttle. Unfortunately, the crew was unaware of the incorrect altitude reading of the left-hand radio altimeter and therefore did not make any corrective actions.

When the aircraft was on the glidepath the auto-throttle moved into the ‘retard flare’ mode, a mode which is normally only activated in the final phase of the landing below 27 feet, as a result of the incorrect altitude reading by the left-hand radio altimeter system. The thrust from both engines was accordingly reduced to a minimum value (approach idle). This mode was shown on the primary flight display as ‘RETARD’. However, the right-hand autopilot, which was activated, was receiving the correct altitude from the right-hand radio altimeter system. Therefore, the autopilot attempted to keep the aircraft flying on the glidepath for as long as possible. This meant that the aircraft’s nose continued to rise, creating
At a height of 750 feet, the crew did not notice that the airspeed fell below the pre-selected speed of 144 knots. When subsequently, the airspeed reached 126 knots, the frame of the airspeed indicator also changed colour and started to flash. The crew also did not respond to several other warning indications. The reduction in speed and excessively high pitch attitude of the aircraft were not recognised until the approach to stall warning (stick shaker) went off at an altitude of 460 feet. This warning is activated shortly before the aircraft reaches a stall situation – a situation in which the wings of the aircraft are not providing sufficient lift and the aircraft is not able to fly anymore\(^1\).

The first officer responded immediately to the stick shaker by pushing the control column forward and also pushing the throttle levers forward. The captain however, also responded to the stick shaker commencing by taking over control. Assumingly the result of this was that the first officer’s selection of thrust was interrupted. Consequently, the auto-throttle, which was not yet switched off, immediately pulled the throttle levers back again to the position where the engines were not providing any significant thrust. Once the captain had taken over control, the auto-throttle was disconnected, but no thrust was selected at that point. Nine seconds after the commencement of the first approach to stall warning, the throttle levers were pushed fully forward, but at that point the aircraft had already stalled and the height of about 350 feet was insufficient for a recovery\(^1\) (Figure 1).

**Air France crashed into the Atlantic Ocean**

On May 31 2009, an Airbus A330-203 (flight AF447) operated by Air France took off from Rio de Janeiro Galeão Airport bound for Paris Charles de Gaulle. Unfortunately, the aircraft never reached destination and crashed into the Atlantic Ocean. The accident cost the lives of 12 crewmembers and 216 passengers\(^2\).

**What caused the aircraft to crash?**

After take-off from Rio de Janeiro Galeão Airport the aircraft was in its cruise flight at FL350 with a cruising speed of 0.8M. During its cruise flight the aircraft entered severe weather conditions causing the pitot tubes to be obstructed with ice crystals leading to an automatic autopilot disconnection and inconsistent airspeed indication. As a result of the inconsistent airspeed indication the Airbus A330 automatically switches to alternate law. When in alternate law, the aircraft no longer has angle of attack (AoA) protection. In aerodynamics, angle of attack specifies the angle between the chord line of the wing of an aircraft and the vector representing the relative motion between the aircraft and the atmosphere. When the AoA is increased too much, the wings will not be able to provide
sufficient lift to keep the aircraft flying (Figure 2). Therefore, an AoA protection is built into the aircraft which limits the input of the pilots so that they cannot increase the AoA too much².

Figure 2: Angle of Attack schematic

The loss of AoA protection had enabled the aircraft to fly with an enormous unconventional degree of pitch. The crew did not succeed to diagnose the inconsistent airspeed and manage it with precautionary measures on the pitch attitude and the thrust. The occurrence of the failure in the context of flight in cruise completely surprised the pilots of flight AF477. The difficulties with aircraft control at high altitude in turbulence led to excessive control inputs in roll and sharp nose-up input by the pilots. The evolution of the pitch attitude and vertical speed was added to the erroneous speed indications and ECAM messages, which complicated the diagnosis of the actual problem. The Electronic Centralised Aircraft Monitor (ECAM) is a system, developed by Airbus, that monitors aircraft functions and relays them to the pilots. It also produces messages detailing failures and in certain cases, lists procedures to undertake to correct them. Unfortunately, the large amount of ECAM messages made it even more difficult for the pilots to understand what problem they were facing. The crew likely never understood that it was faced with a simple loss of airspeed information².

Due to unreliable indication of the airspeed and inappropriate control inputs that destabilized the flight path, the crew seemed confused as to which type of buffet they were experiencing (high Mach number or high AoA). When experiencing high Mach number buffet the aircraft is not able to produce lift anymore as the airflow separates from the aerofoil due to the existence of shockwaves on the wings³. When experiencing high AoA buffet the aircraft is, opposes to high Mach number buffet, flying too slow and as a result of this the wings can not produce sufficient lift. As both pilots of AF 447 did not know to which type of buffet they were experiencing, the aircraft went into a sustained stall. Despite the persistent symptoms, such as stall warnings and erroneous speed indications, the crew never understood that they were stalling and consequently never applied a recovery manoeuvre, causing the aircraft to crash in the Atlantic Ocean² (Figure 3).

Figure 3: Tail section of the Air France flight AF447
Cockpit automation: provide a safe and efficient flight

In general, automation is a process or a task that is executed by a machine or a computer instead of a human\(^4\). In aviation, modern aircraft have become increasingly reliant on cockpit automation to provide a safe and efficient flight and to increase passenger comfort. Furthermore, cockpit automation relieves the pilot from repetitive tasks and reduces pilot workload. The reduction in workload frees attentional resources to focus on more important tasks. Also, cockpit automation makes sure that the aircraft is balanced during the flight which leads to a stable operation and a smooth flight trajectory. Both of these improvements lead to a significant reduction of fuel consumption\(^4\).

Examples of currently automated tasks are: vertical and lateral navigation, fuel and balance optimisation, throttle settings, critical speed calculation and execution of take-off and landing.

The evaluation of cockpit automation

Three generations of cockpit automation, can be distinguished: mechanical, electrical and electronic. In the beginning of commercial flight there were no instrumental aids to help pilots to fly. It took some years for the first instruments to be introduced that could indicate the aircraft’sairspeed and attitude to the pilot\(^5\).

The first signs of automation were introduced on board aircraft during the 1920s and 1930s, in the form of a mechanical pilot that was designed to keep the aircraft flying straight. As airplanes became bigger, the aerodynamic forces increased and it became necessary to apply a form of amplification of the pilots’ physical force by means of pneumatic or hydraulic actuators. Instead of direct control, with the flight yoke mechanically attached to the flight control surfaces, mechanisms were constructed intervening between the pilot’s input and the expected output. At this stage, automation aided pilots mainly in their flying skills.

In the 1960s, plenty of electrical automation was introduced on board aircraft that enhanced flight safety: electric autopilots, auto-throttle, flight directors (used to show pilots how to fly the aircraft to achieve a pre-selected target such as speed and flight path), airborne weather radars, navigation instruments and improved alarming and warning systems capable of detecting several parameters of engines and other equipment\(^5\).

The third generation of cockpit automation involved electronics, and was mainly driven by the availability of cheap, accessible, reliable and usable technology that invaded the market. The electronic revolution occurring from the mid-80s (introduction of the personal computer) also helped to shape a new generation of pilots, who were accustomed with the pervasive presence of technology. Furthermore, electronics helped to diminish the clutter of instruments in the cockpit and allowed for replacing old indicators (round-dial, black and white mechanical indicators for every monitored parameter) with integrated coloured electronic displays. On these displays an overview of multiple parameters could be displayed\(^6\).

Boeing and Airbus: different philosophies

Each airplane manufacturer has a different philosophy on the implementation and use of cockpit automation, so do Airbus and Boeing. Above all, the general agreement is that the flight crew is and will remain ultimately responsible for the safety of the airplane. The significant difference between the design philosophies can be found in envelope protection. Airbus’ philosophy has led to the implementation of “hard” limits, where the flight crew can provide whatever control input desired, but can never exceed the physical limitations of the aircraft. Boeing has “soft” limits, where the flight crew will meet increasing resistance to
control inputs when the airplane is steered out of the normal flight envelope.

In the literature Airbus uses the word ‘operator’ for flight crew, which is in contrast with Boeing that uses the word ‘pilot’ to designate flight crew. The manufacturers’ different definitions of cockpit automation can be defined as follows:

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<th><strong>Airbus</strong></th>
<th><strong>Boeing</strong></th>
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<td>Automation should lead the aircraft through a normal and safe flight envelope and must not work against the operator’s inputs, except when absolutely necessary for safety.</td>
<td>The pilot is the final authority for the operation of the airplane. Only apply automation as a tool to aid the pilot and not to replace the pilot.</td>
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**Automation Bias**

*Automated decision making aid*

Within aircraft, automated decision aids are meant to support human cognitive processes of information analysis and/or response selection in order to help the human user correctly assess a given situation or system state and to respond appropriately. Two different functions of automated decision aids can be distinguished: alerts and recommendations. The alert function makes the user aware of a situational change that might require action. The recommendation function involves advice on choice and action. Within aircraft a Ground Proximity Warning System (GPWS) is a good example of an automated decision aid. The GPWS is designed to alert pilots when the aircraft is in immediate danger of flying into the ground or an obstacle. In such case the system alerts pilots by giving an aural warning (i.e. “caution terrain, caution terrain”) and in some aircraft it also gives a recommendation (i.e. “Pull up! Pull up! Pull up!”).

Two types of errors can occur with automated decision aids: an *error of omission*, or a *commission error*. An *error of omission* refers to a mistake that consist of not doing something you should have done, or not including something such as an amount or fact that should be included. A *commission error* refers to a mistake that consists of doing something wrong, such as including a wrong amount in the wrong place. In terms of automated decision aids, an *error of omission* refers to the user that does not respond to a critical situation, relating to the alert function. A *commission error* is related to the specific recommendations or directives provided by an aid. In this case, users follow the advice of the aid even though it is incorrect.

**Definition of automation bias**

Quite often, users of automated systems have a tendency to ascribe greater power and authority to automated systems than to other sources of advice. In other words; users of automated systems prefer the outcome and recommendations of an automated systems rather than other sources (for example their own knowledge and expertise) of information.

According to Mosier and Skitka (1996) automation bias can be defined as phenomena resulting from people using the outcome of a decision aid “as a heuristic replacement for a more effortful process of information analysis and evaluation”. Automation bias refers to phenomena caused by the increased thrust that people have in automated systems.

**Phenomena that contribute to the occurrence of automation bias**

Three main factors of automation bias have been assumed to contribute to the occurrence of automation bias:
1. One is the favour to use automated recommendations and directives as a replacement for a more effortful process of information analysis and evaluation.

2. A second factor is the perceived trust of humans in automated systems. A side-effect of this factor is the phenomenon referred to as complacency. In the aviation community, complacency refers to situations in which pilots, air traffic controllers, or other operators purportedly did not conduct sufficient checks of system states and assumes “all was well” when in fact a dangerous condition was developing that led to the accident. A side-effect of this factor is the phenomenon referred to as complacency. In the aviation community, complacency refers to situations in which pilots, air traffic controllers, or other operators purportedly did not conduct sufficient checks of system states and assumes “all was well” when in fact a dangerous condition was developing that led to the accident.

3. The third factor is diffusion of responsibility; whereby social loafing can occur. Social loafing refers to the tendency of humans to reduce their own effort when working redundantly within a group (or with an automated system) than when they work individually.

These factors mainly arise when the user has often experienced reliable automation. These factors are inconsequential as long as the automation maintains reliability. However, performance of automation users can compromise considerably in case of automation failures, that is, if the system does not alert the user to become active, if the system provides a false recommendation or directive or if the automated system does not operate properly.

**The duration of automation bias**

Boer, Heems and Hurts (2014) have performed a study aimed at quantifying the duration of automation bias. The objective of their study was to find how long automation bias phenomena persists and which factors influences its duration, by means of simulating malfunctions in a simulator. They found that the duration of failure detection for licensed pilots varied from 18 sec to over 720 sec. with only 11% of the participants meeting the standard for the detection of visible alarms of 23 to 45 sec. In addition, they also found a significant difference in the sensitivity to automation bias between junior and experienced pilots. Less experienced pilots are on average less sensitive to automation bias but have more variation in performance than more experienced pilots.

**Automation bias involved in Turkish Airlines flight TK1951**

Turkish Airlines flight TK1951 intercepted the localizer signal at 5.5 NM from the runway threshold at an altitude of 2000 feet. Therefore, the glideslope had to be intercepted from above rather than the preferred intercept from below. As a result, the crew was forced to carry out a number of additional procedures, resulting in a greater workload. This also caused the landing checklist to be completed during a later moment in the approach than standard operational procedures prescribe.

The cockpit crew did not have information regarding the interrelationship between the (failure of the) left radio altimeter system and the operation of the auto-throttle readily available. Of all the available indications and warning signals, only a single indication referred to the incorrect auto-throttle mode, namely ‘RETARD’ annunciation on the primary flight displays. As a result of the greater workload, the incorrect operation of the auto-throttle was obscured for the crew. Despite the indications in the cockpit, the cockpit crew did not notice the large decrease in airspeed until the approach-to-stall warning.

With the cockpit crew – including the safety pilot – working to complete the landing checklist, no one was focussing on the primary task: monitoring the flight path and the airspeed of the aircraft. This task was performed by the automated system and it is assumed that the flight crew stated that all was well, when in fact a dangerous situation was happening. This can be referred to as the second factor of automation bias: the perceived trust of humans in automated systems.

**Automation bias involved in Air France flight AF447**

The obstruction of the pitot tube with ice resulted in an inconsistent airspeed indication and a loss of AoA protection. The fact that the high AoA situation was not identified by the Pilot Flying (PF) while he was
continuously pulling on the control stick seems to indicate that he may have embraced the common belief that the aircraft could not stall, and in this context a stall warning was inconsistent. This is again an example of the perceived trust of human users in automation, which lead to a fatal accident.

A second bias involved to this flight is an error of omission, with the crew not responding to the alert function of the aircraft (i.e. stall warnings and speed warnings).

Automation Surprise

Automation technology was originally developed to increase precision and economy of operations while, at the same time, reducing operator workload and training requirements. It was considered possible to create an autonomous system that required little human involvement and therefore reduced or eliminated the opportunity for human error. Within this type of automated systems, the computer performs more and more human-related functions and operations, with the possible consequence that humans have less interaction with the system\textsuperscript{12}. The human user can become less aware of the system operations and eventually be “out-of-the-loop”. When the human is out-of-the-loop, the engagement to the process is significantly reduced causing the human user to experience, due to automation, limited access to relevant information in a given situation\textsuperscript{8}. Their ability to detect problems, determine the current state of the system, understand what has happened and what courses of actions are needed, and react to the situation will decrease. This phenomenon can be described as loss of situational awareness\textsuperscript{13}.

The results can be situations where the operator is surprised by the behaviour of the automation asking questions like, what is it doing now, why did it do that, or what is it going to do next\textsuperscript{12}. Thus, automation has created surprises for human operators who are confronted with unpredictable and difficult to understand system behaviour.

Automation surprise involved in Turkish Airlines flight TK1951

During the approach the aircraft was already in landing configuration with gear down and flaps extended more than 15 degrees. This configuration along with the wrong height indication of ~8 feet by the leading left radio altimeter system, caused the auto-throttle to be set in ‘Retard flare mode’.

On the one hand, a primary cause which led to the fatal accident is the failure of the crew to monitor the flight path and the airspeed of the aircraft. On the other hand, the automatic switch to the ‘Retard Flare Mode’ on a height greater than 27 feet as a result of the failure of the left radio altimeter system might have surprised the pilots and caused an additional pressure on the already extra high workload.

The aviation industry was already familiar with the possible failure of the radio altimeter system and its subsequent actions, but it was assumed that the pilots would easily manage and recover from this situation. Several airlines, including Turkish Airlines, regarded the problems with the radio altimeter as a technical problem rather than a hazard to flight safety. As a result, the pilots were not informed of this issue.

Automation surprise involved in Air France flight AF447

The Airbus A330’s Fly-By-Wire (FBW) system is so designed that when in an abnormal condition, the system will automatically switch to a so called ‘Alternate Law’ mode. In this mode the AoA protection will be disengaged and the aircraft will be able to fly a high degree of pitch. The occurrence of automation surprise is exemplified in this accident for two reasons: the first reason is the fact that the pilot failed to correctly link the stall warning with the airplane’s attitude under alternate law. The second reason is the fact that the pilot monitoring did not understand why the aircraft was seemingly not responding to its input, as the pilot monitoring was also giving input to the controls.
Improving human-cockpit automation interaction

Rethinking pilot training
One of the conclusions that can be drawn from the report on flight AF447 is that flight training simulators should be improved in such a way that they can reproduce realistic scenarios of abnormal situation. Furthermore, the training scenarios should ensure the effects of automation surprise in order to train pilots to face these phenomena\(^1\).

Several publications provide recommendation on how to improve pilot training. For example, Gray (2007) refers to evidence that pilots are not being trained to a level that enables them to use automated systems in all circumstances. He states that pilots should be trained to understand when automated systems should be discarded and the pilots should revert to manual control\(^1\).

Although the daily routine of flying is driven by automation, the laws of physics have not changed. Basic flying skills need to be trained to build a strong foundation that every pilot can fall back to when necessary\(^1\). Antonovich (2008) recommends that pilot training should train the pilot to analyse the influences of automation, so that they are better prepared to deal with the problems associated with automation and maintain greater situational awareness during the flight\(^1\).

The European Aviation Safety Agency (EASA) performed a questionnaire among more than 150 respondents, mostly airline pilots from Europe, that substantiate these views. EASA concluded from its questionnaire that basic and manual flying skills tend to decline because of the lack of practice. Furthermore, the pilot interaction with automation, the selection of different flight modes, can distract the pilot from the actual flying. The overall recommendation in the report is to improve basic airmanship and manual flying skills of the pilots. It is also stated that recurrent training and testing practices with regard to automation management should be improved\(^1\).

Redefining the role of the pilot
Another option that can lead to significant improvements in human-cockpit automation interaction, is improving and simplifying current cockpit design. Two different approaches in cockpit design have been proposed by Letsu-Dake et al (2012): Pilot as Pilot and pilot as manager.

Pilot as pilot
In the Pilot as Pilot approach the cockpit design intends to support the flight crew in their conventional role as pilots. The flight crew is actively engaged in flight control with the final authority and responsibility over the aircraft. In this design the pilot stands above the cockpit automation, and can authorize and delegate tasks to the cockpit automation and can take back manual control over the aircraft at any moment during flight and ground operation. The cockpit layout, functions and formats, are designed in such a way that the pilot is able to make tactical decisions in the planning of the flight. The interfaces of the functions are simplified and provide the pilot with necessary information and decision proposals\(^2\).

In the Pilot as Pilot cockpit design two key positive and negative implications have been identified. One of the key positive implications in this design is that it is based on traditional human-centred design principles. It appears that humans perform better in emergency situations when they have been actively involved in performing relevant tasks during normal flight conditions. A negative aspect in this design relates to higher workload resulting from the active involvement in relevant tasks. The higher workload might negatively influence the ability of pilots to perform in an increasingly complex environment with a great demand for precision and efficiency and small safety margins\(^1\).

Pilot as manager
In the approach of design where the pilot acts as a manager the flight crew will share authority and responsibility with automated systems for factors such as safety, efficiency and passenger comfort. Most of flight tasks will be...
executed by cockpit automation and managed by the flight crew. Cockpit automation is in this case responsible for most of the aircraft control and information processing. What is necessary for this approach is extremely reliable and highly capable cockpit automation that is able to perform current cockpit functions. Situation assessment and tactical flight planning are shared responsibilities between the pilot and automation\textsuperscript{19}.

Just like in the Pilot as Pilot approach the Pilot as Manager approach has some key positive and negative implications. One of the main positive implication is that the flight crew will have greater bandwidth to manage all aspects of the flight, because they are not spending time, effort and pay attention on performing lower level manual tasks. A negative side of the pilot in the role of manager is to keep the flight crew engaged in the flying process. Actively performing tasks is known to be more engaging than managing tasks. The challenge is to make the flight crew behave actively instead of passively and be fully involved\textsuperscript{19}.

**Does automation improve or reduce aviation safety?**

In general, cockpit automation improves overall aviation safety. Modern aircraft are increasingly reliant on automation for safe and efficient operations. Automation has brought significant advantages for flight safety and operations. However, automation can be challenging for instance to senior pilots who may be less comfortable with automation while the new generation of pilots may lack basic flying skills when the automation disconnects or fails or when there is a need to revert to a lower level of automation, including hand flying the aircraft\textsuperscript{14}. Improved pilot training and strict role definition could improve aviation safety even more.

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**Glossary**

- **Angle of Attack**: In aerodynamics, angle of attack specifies the angle between the chord line of the wing of fixed-wing aircraft and the vector representing the relative motion between the aircraft and the atmosphere.

- **Aerodynamic(s)**: dynamics of bodies moving relative to gases, especially the interaction of moving objects with the atmosphere.

- **Automation bias**: Phenomena resulting from people’s using the outcome of a decision aid “as a heuristic replacement for a more effortful process of information analysis and evaluation.”

- **Automation surprise**: Situations where the operator is surprised by the behaviour of the automation asking questions like, what is it doing now, why did it do that, or what is it going to do next?

- **Commission error**: refers to a mistake that consists of doing something wrong, such as including a wrong amount in the wrong place.

- **Complacency**: refers to accidents or incidents in which pilots, air traffic controllers, or other operators purportedly did not conduct sufficient checks of system state and assumes “all was well” when in fact a dangerous condition was developing that led to the accident.

- **Error of omission**: refers to a mistake that consist of not doing something you should have done, or not including something such as an amount or fact that should be included.

- **Flight trajectory**: precise route taken or due to be taken through the air by an aircraft.
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- **Out-of-the-loop**: Reduced human engagement to a process.
- **Situational awareness**: the ability to detect problems, determine the current state of the system, understand what has happened and what courses of actions are needed, and react to the situation.
- **Social loafing**: refers to the tendency of humans to reduce their own effort when working redundantly within a group (or with an automated system) than when they work individually.
- **Stall**: A stall is what happens when an aerofoil can not provide sufficient lift in order to keep the aircraft in level flight.

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**Image references (top to bottom, left to right)**


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