AIRCRAFT DESIGN: 
REAL LIFE EXAMPLES IN EDUCATION

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Abstract. This paper deals with methods of teaching aircraft design based on the extensive use of actual case studies to contribute to the consolidation of course material and increase student interest and participation.

1 INTRODUCTION

The course Aircraft Design for students enrolled in Aeronautics is certainly one of the most basic but it also quite difficult as it usually (more-or-less) unites almost all of the disciplines which students learn in this discipline (Figure 1).

Given the high degree of integrality of design as an area of study, it demands the commitment of a large number of hours devoted to both the theoretical and practical aspects of the content. This commitment is often seen by many students as not allowing enough breathing room for its successful assimilation. In this regard, the teacher has to think about how to interest students so as to attract the attention of often weary young people to interact with this difficult field of study. It is no secret that every teacher believes that his discipline is the most
important, but it is the student that has the rather difficult task of equally dividing his time between all the courses that he has to undertake. I think it fair to say that the design is not only a science but also an art. Design, in addition to its scientific foundation, also requires that the student has some artistic abilities. Maybe that's why General Designer of the Sukhoi Bureau, Mikhail Simonov, was awarded the State Prize of the Russian Federation for technical design in the field of literature and art for the Su-27. All over the world, this aircraft is perceived as a work of art. The second prize was awarded to the Su-26 for sport and aerobatic aircraft. This aircraft is also considered an example of high art - the art of aircraft design.

A great aircraft designer said a simple but very accurate phrase about such aircraft (Fig.2) - "Only the beautiful planes fly well".

So, how do we help the students, the future designers, learn how to create beautiful airplanes? How do we attract them to the complex, but surprisingly interesting Good fly only the beautiful planes of design? How do we encourage and foster informal learning? An essential element is the interest of the students.

One idea is for the teacher to use real-life examples during the course of teaching design to provoke interest. Often when a student begins to hear about the comic and sometimes tragic cases that occur with projects or with aircraft in service, a previously dormant interest is awakened and the students begin to show real interest, sometimes to an animated degree. There are many reasons why this happens:

Firstly, much of the subject to be covered is theoretical and of a purely scientific nature, so the application or reality of it may not necessarily be immediately obvious to the student. The teacher, more often than not, does not have enough time to cover 100 percent of the course material. The onus then, lies with the student. Since aviation has become a necessary and commonplace attribute of modern life of which most students will have taken part in, the very use of this most rapid of transport systems by the student should cause them to wonder, "what if..." This is a most interesting thing for the teacher to hear, as the student is thinking of things that they would have not previously considered, whether it is an aspect of design, operation, malfunction, or simply as in to use the equipment or vehicle as a passenger.

So, the purpose of the examples which we might use from the very beginning should make the course more attractive, interesting and informative.
Moreover, the analysis of these situations may apply to all stages of the life cycle of the aircraft: design at all stages (development requirements and the formation of technical specifications, the technical proposal, preliminary design, technical design); production; testing and refinement; exploitation; after the operational period – Fig.3

2 EXAMPLES AND ANALYSIS

Let us discuss some memorable examples that can be used in teaching the course Aircraft Design in its various sections.

Example 1. Selecting an aircraft concept.

The purpose for which a Flight Vehicle (FV) will be used largely determines its general configuration and systems. This is essentially the beginning of the project and it includes the selection and mutual spatial link parts of the whole system, its components and assemblies, their external forms and construction, design of the crew spaces, passenger and cargo areas and capacities, equipment, fuel and engines. Referring to the most expensive aircraft, which took 12 years before the first flight, which operated for 30 years and during this time continued to be refined, and then took its rightful place in the best exhibition halls. It is the reusable aerospace system, the Space Shuttle. Figure 4.

From Fig. 4, we see how dramatically the appearance of the aircraft can change during concept development. The reason in this case was the significant reduction in funding for this

Figure 4: Changing the concept of reusable system "Space Shuttle" in the design:

a – model at an early stage; b – the final version of the system
program. Developers analyzed hundreds of different options ranging from fully saved with LRE and SRE, with various forms of ASP wings, with the possibility of using a turbojet engine in the return phase of flight. As a result of lower funding, designers had to significantly reduce the mass of the system, so that all of the sustainer fuel for the liquid rocket engines was held in a disposable fuel tank. In the final version of the Space Shuttle, it took the form shown in Fig.4b.

Example 2. To select the FV layout.

Modern aircraft design has evolved to the point now where is a fairly stable range of possible conventional forms of aircraft, designed for a multitude of different purposes. History however, as even a brief internet search will reveal, shows many examples of aircraft design that most definitely do not fit into the conventional design basket. A brief stop to inspect some of these interesting creatures is assured to greatly enliven any audience, no matter how tired they may be.

The examples in Fig.5-6 may also contribute to the development of the students'non-standard thinking, a quality which may prove useful in creating breakthrough projects in which traditional schemes have already been proven ineffective.

Example 3. Atmosphere in a spaceship.

When the concept of a manned spacecraft was conceived, the most fundamentally important question to be answered was that of the atmosphere inside the spacecraft's cabin. Since neither Soviet nor American designers had any actual experience in the matter, they unsurprisingly followed different paths to solve the problem.
American ships' life support systems were calculated at 0.035 MPa pressure. In preparation for the start, and at the start of the flight, the atmosphere in the cockpit consists of 60% oxygen and 40% nitrogen, the mixture in the air vented and replaced by pure oxygen. Soviet ships were designed with an on-board atmosphere, composition and pressure close to that of the earth.

This begs the question: "which is better?"... not an easy question to answer. The American designers started from the principle of "less": on the positive side the design meant lower weights overall, but on the the negative side, the volatility of a pure oxygen environment greatly reduced fire safety. The large mass of Soviet ships reduced the fire problem in the case of a short circuit, leakage of fuel and other emergency situations that may present the possibility of a fire.

The susceptibility of the American system to the very real dangers of an on-board fire were sadly realized on January 27, 1967, when, during a ground test on board Apollo 1, a short-circuit led to an instantaneous ignition of the pure oxygen environment. Other flammable items in the crew space - nylon netting and foam pads - also quickly ignited. The entire crew: Virgil Grissom, Edward White and Roger Chaffee, trapped by a cabin door system that was difficult to operate, especially under duress, all perished in an instant. It became clear that this fundamental problem could been solved on a conceptual level, but at this stage it was too late to redesign the ship. Nevertheless, the Apollo flight program successfully completed 6 manned moon landings.

The problem emerged again on during the Apollo 13 moon mission. This expedition can be viewed in any training course as an example of the courage and heroism of the astronauts, the ground crew and the leaders of the flight, and the ability to adapt and solve intense and difficult problems under extreme duress.

On April 11, 1970, the Apollo 13 mission launched from the Kennedy Space Centre in Florida. On April 14, at a distance of approximately 330,000 km from Earth, one of three fuel cells, cryogenic oxygen tanks, in the Service Module, exploded. The subsequent failure of the remaining two fuel cells (within about 3 minutes of the initial explosion) that provided the power supply to the Command Module of the crew compartment meant that the crew had to move into the Lunar module to survive. Using the undamaged engine and the moon's gravity, the Apollo 13 crew adjusted the ships trajectory so that after the orbit of the moon, the ship successfully returned to earth.
Example 4: Historical docking in orbit

An interesting solution was arrived at by Soviet and American designers with the historical event of the first international ships docking in orbit, Apollo 21 and Soyuz-19 July 17, 1975 - Fig. 7. A serious problem was the different pressures within the spacecraft. To solve it, a compartment was added to Apollo where the Lunar Module would have normally been situated. After docking, the pressure in this compartment was increased to 520 mm (from 280 mm of mercury). In the Soyuz, working pressure was reduced to 520 mm. The command module of Apollo remained at its normal level of (low) pressure but it had to be sealed for the duration of the docking with a single astronaut inside.

In terms of methodology, it is an interesting task for practical lessons about design, when students are invited to solve a particular problem, followed by an analysis of the advantages and disadvantages of each of the proposed options. For example, when analyzing the weight of spacecraft structures, one method would be to investigate the advantages and disadvantages of the reduced structural mass allowed by decreasing the internal pressure, as opposed to the effects of the increased structural mass required to accommodate the higher internal pressures of an earth-like atmosphere.

Example 5. rescue crews in emergency situations

To create plenty of student interest when studying military aircraft, the analysis of the issue of emergency crew evacuation will generate a lot of spectacular images. There are numerous positive examples that one could use, as well as some controversial ones which may cause the student to reflect somewhat longer.

One such example is the crew emergency evacuation system for the Tupolev Tu-22 supersonic bomber (Figure 8).

Figure 8: The Tu-22 and its ejection seats

In a complete reversal of conventional thinking, the three ejectionseats of the Tu-22 are fired downwards. This creates severe height restrictions when ejecting from the aircraft. Crew ejection can only be attempted above 230-245m in horizontal flight, and 340m in the planning with the engine off. For emergency evacuation from the airplane after a belly landing or other emergencies that might occur on the ground, the crew of three would have to use the top hatches. As they say “The rescue of drowning is the handiwork of drowning”.

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Unusual ejection procedures aside, overall the Tu-22 was not considered a success. The aircraft was very difficult to fly, had uncomfortable seats, a much higher landing speed than previous aircraft, and very poor all-round visibility that significantly impeded the pilots' ability, particularly during takeoff and landing. The plane did not forgive the slightest error of pilots. Pilots nicknamed the plane "awl", which indicated a mutual dislike between aircraft and pilot. General Designer Andrey Tupolev had created more than 300 projects, most of which have been implemented (Figure 9), but he considered this aircraft one of his most unfortunate. As the saying goes, "every family has its black sheep." However, thanks to the lessons learnt from these errors, Tupolev's design Bureau were able to create such unique bombers like the Tu-22M3, Tu-160, some of the characteristics of which are still considered the benchmark for that type of aircraft.

Example 6. From ancient times to the present day

Any section of design can be made more fun and interesting by analyzing the historical development of the topic. Another example is also associated with the concept of an emergency ejection system from aircraft (Fig.10-11). After the disaster of the Challenger space shuttle, which exploded shortly after take-off with seven astronauts on board, the developers went back to looking at emergency rescue systems. The new space shuttle, Columbia, was fitted with ejection seats for two crew members, but even though the space shuttle system has been retired, the question of how to provide a conceptual solution to the problem of safely leaving the reusable spacecraft in the case of emergency situation at all altitudes and speeds remains a viable challenge for future designers. (Figure 12) This issue still requires careful consideration and you can offer students a wide field of creativity for their unblinking consciousness to come up with answers.
Analysis of aircraft accidents clearly shows that most of the problems come down to human error. Most often, these incidents are attributable to failures in communication. Miscommunication is the leading factor in over 70% of runway incursion incidents: pilots, controllers, maintenance staff and the like moving around airports, must use radios and other electronic devices to communicate, and mishearing or misunderstanding directives or messages can lead to disaster.

An example of such a fatal mistake – the largest aviation disaster in the world, occurred at Teneriffe in the Canary Islands in 1977. A collision between two Boeing 747s, KLM 4805 which was taking off, and Pan-Am 1736 that was taxiing toward him on the runway, killed 583 people. The runway was shrouded in thick fog and the taxiways were clogged with parked aircraft that had been diverted there due to a bomb explosion at their destination, the nearby Las Palmas airport. The KLM Captain made the disastrously mistaken assumptions that the runway was clear and that they were cleared to take off. Neither assumption was correct and the KLM 747 struck the Pan Am jet at approximately 260kmh, resulting in everybody on KLM being killed, with 61 survivors from the Pan Am aircraft.

It was this single disastrous accident that reinforced the reality that pilots and controllers rely almost exclusively on voice communications, and that effective verbal communication is essential for ensuring safety in civil aviation. As a result, a standardized phraseology for aviation has been developed, focusing on an absence of grammar, complexity and ambiguity, and consisting of simple, clear messages that are sufficient to communicate 95% of what pilots and controllers need to say to each other.

Human error can also be a factor in areas where the aircraft has suffered some kind of failure of its systems or structure. Graduating students are often lead to find work at airports, being involved in repair or maintenance. Both of these areas are vital in maintaining the reliability and integrity of the original design.

To use another tragic example, I draw your attention to the 1985 crash of a Japan Airlines Boeing 747. Due to a poor quality repair from a tail-strike incident during landing some 7 years earlier, the aircraft suffered a major structural failure in flight, and the resulting crash claimed the lives of all but 4 of the 524 people on board. It would seem that in such situations, the designer is helpless, as not only were correct procedures to effect the repair not followed,
but the inspection of the repair work did not reveal the improper repair, and the aircraft was put back into service.

However, to reduce the risk of possible structural failure, it is no coincidence that experienced designers always considered various kinds of non-standard situations to ensure their designs are foolproof. Before the widespread advent of computers, designers were forced to be more sensitive to the practical aspects of construction and maintenance. Now, a fair greater amount of time is dedicated to analyzing results of design arrived at by computer modelling. Sometimes, this has had the opposite effect of actually making the design process more complicated rather than making it easier.

However, as in the past (in the pre-computer era), much depends on a confluence of circumstances, as is often said, "from the fate."

Which brings us to our next example:

**Example 7. Freezing o-ring seals: the Challenger catastrophe**

On the morning of 28th January, 1986, temperatures at the Kennedy Space Centre at Cape Canaveral, Florida, had dropped below freezing. At 11:38am that morning, after a six day delay due to weather and technical problems, the 25th space shuttle mission was launched. The launch had attracted more media attention than usual, as it was carrying the first school teacher to go into space. Christa McAuliffe was planning to give lessons to children in schools throughout the US while she was in orbit.

Earlier, engineers had warned their superiors that the rubber O-rings that sealed the joints of the shuttle’s solid rocket boosters were vulnerable to failure at low temperatures. However, these warnings went unheeded, and Challenger lifted off. 73 seconds into the flight, amid great columns of smoke and fire, Challenger broke apart before the disbelieving eyes of the hundreds of onlookers (including the families of the crew) who had gathered to watch the launch, as well as the millions watching on live television, and plunged into the ocean. All seven astronauts on board had perished in an instant.

The destruction of the aircraft was caused by damage to the sealing ring on the right solid rocket booster. The resultant hole in the side of the booster, and a powerful jet stream in the direction of the external fuel tank destroyed the tail mount of right solid rocket booster and the load-carrying structures of the external fuel tank. Elements of the complex began to move relative to each other. This was followed by the destruction of the external fuel tank and the detonation of the fuel components.

At the conclusion of the commission of inquiry into the disaster, it was found that NASA managers had not paid enough attention to the potentially dangerous effects of the failure of the sealing rings. They also ignored warnings about the dangers of launching the ship during periods of very low temperatures, as were experienced on the morning of the launch.

The commission also found that Morton Thiokol, the company that designed the solid rocket boosters, had ignored warnings about potential issues, and that NASA managers were aware of these design problems but also failed to take action.
Thus the root cause of the problem that precipitated this whole tragic chain of events lies in the fact that the designers designed a poor system to connect the different sections of the solid booster.

**Example 8. Thermal protection concepts**

The second Space Shuttle disaster almost forced the premature closure of the entire Space Shuttle program. The main culprit for this tragedy was the unreliable operation of the Thermal Protection System (TPS) of the spacecraft during re-entry.

On 1 February 2003, shortly before the successful completion of the 107th Space Shuttle mission, air-spacecraft Columbia, carrying seven astronauts, disintegrated during re-entry to the earth's atmosphere. The main parts of Columbia's TPS consisted of tiles of thermal insulation foam made from ceramic fibres able to withstand temperatures of up to 1250°C, and carbon-carbon panels on the leading edge of the wing, rated to withstand temperatures of up to 1650°C. The lower boundary of this corridor is associated with two restrictions: strength restriction defined by the maximum normal overload $n_y \leq 2.5$ and thermal restriction connected with the maximal temperature of the vehicle surface $T_{\text{max}} \leq 1650°C$ (Fig. 14, a).

According to official report, a flow of hotgas of several thousand degrees forced its way through a damaged thermal insulation tile on the leading edge of the left wing and into the wing structure. The load-bearing structure of the wing sections were made of aluminum alloys which, without insulation, would start to lose their load-bearing capabilities at 300°C, and at 650°C, would start to melt and disintegrate. Mission control noticed abnormally high temperatures coming from sensors in the left wing, and then increasing tire pressures in the landing gear, followed by the loss of the sensors.

With a temperature now several times that of which it could withstand, the wing structure began to break up and then separate from the ship, resulting in Columbia rolling and bucking out of control. Evidence indicates that the crew was conscious at this point and aware of the increasing temperature and loss of control, however at an altitude of 60 km and a speed of 20,160km/h (5.6 km/s), Columbia's main cabin structure began to break apart some 40 seconds after the separation of the left wing. The immediate depressurization of the crew
spaces as they broke apart meant that the crew were knocked unconscious or killed at that instant.

If we return to the launch of Columbia's final mission on 16th January 2003 (Fig.14, b), it was found that at an altitude of 20-km, a piece of insulation 0.5x0.375x0.125 m was shed from the pylon of the external fuel tank of the Shuttle, which at this stage of the flight was moving at 785 m/s. The piece was entrained by the streamlining flow and reached acceleration of 10g relative to the Shuttle. Having passed almost a half of the spacecraft's length and having attained the speed of about 220 m/s, the foam hit the left wing's leading edge and crumbled to pieces.

This process was simulated in the laboratory afterwards using a gas gun, and the results shocked everybody. A large hole was punched in the carbon thermal insulation of the horseshoe-shaped leading edge of the wing. It is impossible to reproduce a real flight in laboratory environment, but all the same one can not get rid of the feeling that experimenters had overdone it.

This disaster can be used to deal with different perspectives: reliability, durability, heat transfer, and overall design. However, the question as to the ideal thermal protection system remains.

![Figure 14: The Columbia disaster: a – trajectory of re-entry of orbiter; b – chain of events that disrupted the thermal protection system](image)

It is unacceptable responsible places design errors. It is no accident the safety factor increases for them. But, as experience shows, the error is almost always inevitable. The question is how to be on time to find and fix.

In some cases, the absolute best design errors are invisible and can be shown not at once, or only when a particular set of circumstances.

**Example 9. Fatigue design.**

In 1972, an Antonov An-10 carrying 122 people, began its approach to land at Kharkov airport, Ukraine. At an altitude of 1700 meters, the ship suddenly began to crumble apart.

The investigation showed that the cause of the disaster was a massive structural failure of
the center wing section due to a fatigue crack in the lower central wing panel. The crack began to grow rapidly in both sides of the panel and then moved to longerons. As a result, both wings separated from the fuselage causing the fuselage to crash into a wooded area below.

The An-10 was designed for general technical resource of 20,000 flight hours and 12,000 cycles. At the time of the incident the aircraft had been in operation for 11 years, and had flown about 15,500 hours, completing more than 11,000 cycles. Following this accident, an investigation revealed fatigue cracking of the wing centre-section stringers on many of the remaining An-10s in service. The operator of the aircraft, Aeroflot, withdrew the An-10 from passenger services. 25 an-10 aircraft deemed to be in good condition were transferred to the VVS (Soviet Air Force) and other government units, but even these remaining aircraft were retired by 1974, with many examples being donated to museums, parks and several were converted into children's theatres.

Example 10. Wear design

The Yakolev Yak-42 is a three-engined, low-wing, all-metal monoplane with a design lifespan of 30,000 one-hour flights. With a passenger capacity of around 100+ people, it was designed as a short-medium haul airliner which came into service at the end of 1980. Not unusually for aircraft with rear-fuselage mounted engines, the Yak-42 featured a T-tail, an emmpennage configuration where the tailplane is mounted on top of the vertical stabiliser.

In 1982, an Aeroflot Yak-42 crashed in Belarus, killing all 132 people on board. The cause was found to be a failure of the aircraft's jackscrew mechanism from metal fatigue which resulted from flaws in the Yak-42's design. The failure of the mechanism and resulting loss of control put the aircraft into a steep dive thus exceeding the aircraft's design loads, at which point it began to break up mid-air. The accident aircraft had only been in service for less than a year, with approximately 800 hours total flying time. As a consequence, all Yak-42's were temporarily withdrawn from service until the design defect was fixed, returning into service some 2 years later.

This crash has haunting similarities to the crash of another T-tail aircraft in 2000, the McDonnell Douglas MD80, flown by Alaska Airlines. Once again, the jackscrew failed and sent the aircraft into a steep dive. Initially the pilots were able to regain control and make plans for an emergency landing. However, shortly after stabilising the aircraft, the jackscrew failed completely. The pilots were unable to control the aircraft, and it dived inverted into the Pacific Ocean, killing all 88 on board.

In both cases, the design and maintenance of the jackscrew and acme nut assembly were found to be at fault. In the Alaska Air case, an Alaska Air mechanic had recommended in 1997, 3 years prior, that the jackscrew mechanism in the accident aircraft be replaced due to it showing excessive wear. This recommendation was ignored and the aircraft continued in service, and the inadequate maintenance procedures followed by the airline continued until uncovered by the resultant investigation.
3 CONCLUSION

We could continue to recount similar examples almost indefinitely, all of which can be useful in varying degrees, to those who seek to study the art and discipline of design, and to those who want to create systems, be they simple or complex, and make them as safe and as effective as possible.

Communicating with students who have graduated from university more than 30 years ago, many say that such examples still remain in their memory and are still a good guide for them as they progress through a career in design.