



# Major Structural Modifications on a Boeing 777-200LR Fuselage

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Thesis to obtain the Master of Science Degree in

# Aerospace Engineering

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# January 2021

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# Acknowledgments

Firstly I want to thank my master thesis coordinator, Professor Afzal Suleman, for having presented to me the opportunity of doing an internship in Jet Aviation, and for guiding me throughout the entire duration of my work.

Secondly, I want to thank my Jet Aviation supervisor Eng. Tomás Ferreira, who was always available to help me whenever I needed, having integrated me into the team since the beginning. Furthermore I want to thank the company itself, Jet Aviation, for having given me the opportunity of conducting my master thesis while doing the internship, and for providing me with the tools and training to do so.

Finally I want to thank my family for the constant support throughout the years, and for having helped me during the months I was in Switzerland, especially in a year like 2020. I also want to thank my friends for having accompanied me during these past five years, especially Joana Silva, who never gave up on supporting me.

# Resumo

A evolução exponencial da indústria aeronáutica no último século veio trazer novas oportunidades de mercado, como por exemplo as modificações nas aeronaves. Quer se trate de uma reparação ou alteração, estas modificações devem ser certificadas, pela empresa que as realiza ou, caso não tenham privilégio para tal, por uma agência reguladora como a *European Union Aviation Safety Agency* (EASA) ou a *Federal Aviation Administration* (FAA), por meio do uso de um *Supplemental Type Certificate* (STC). Esta tese retrata duas *major modifications* : i) uma antena *Ka-band*, que permite um acesso sem fios à internet e ii) uma câmara *quad* utilizada para entretenimento dos passageiros, permitindo a visualização do exterior da aeronave. Em ambas foi feita uma definição cuidadosa e detalhada do local de instalação no avião, por ser considerada uma das chaves para o sucesso do *design*. Todas as componentes estruturais são produzidas pela *Jet Aviation*, para ambas as instalações, embora na integração da antena de *Ka-band* haja a orientação adicional do *standard* de indústria *Aeronautical Radio Incorporated* (ARINC) 791. Três variações de *design* na câmara *quad* são estudadas através do método dos elementos finitos, a fim de obter uma redução de peso e custo da instalação, mantendo a integridade estrutural. Finalmente são apresentados os documentos necessários para realizar a candidatura ao STC.

**Palavras-chave:** Modificações estruturais, Antena *Ka-band*, Câmara *quad*, *Design* estrutural, Análise estática, Certificação de modificações

# Abstract

The exponential evolution in the aeronautic industry in the last century opened the market for new business opportunities such as aircraft modifications. Whether it is a repair or an alteration, these modifications must be certified, by the company that is doing them or, in case they do not have the privileges to do so, by a regulatory agency such as the European Union Aviation Safety Agency (EASA) or the Federal Aviation Administration (FAA), through the use of a Supplemental Type Certificate (STC). In this thesis, two major modifications are presented : i) a Ka-band antenna, used for wireless internet access and ii) a quad camera used for passenger entertainment. For both cases, a careful and detailed aircraft environment definition, at the installation area, is done, since it is considered to be one of the keys for design success. All structural provisions are produced by Jet Aviation, in-house, for both installations, although for the Ka-band antenna integration there is the additional guidance from the industry standard Aeronautical Radio Incorporated (ARINC) 791. Three quad camera design variations are studied by using the finite element method (FEM), in order to achieve a weight and cost reduction, while maintaining the structural integrity. Finally the important documents needed in order to apply for the STC are presented.

**Keywords:** Aircraft modifications, Ka-band antenna, Quad camera, Structural design, Static analysis, Modification certification

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# Nomenclature

# Greek symbols

$\sigma_C$	Total circumferential stress.
$\sigma_L$	Total longitudinal stress
$\sigma_{bending}$	Bending stress.
$\sigma_{circ}$	Circumferential stress.
$\sigma_{long}$	Longitudinal stress.
$\sigma_{S_u}$	Ultimate shear stress.
$\sigma_{T_u}$	Ultimate tensile stress.
$\sigma_{VM_{max}}$	Maximum Von Mises stress.

# Roman symbols

$A_f$	Fastener cross section area.
$A_p$	Fuselage projected area.
$A_r$	Camera reference area.
$A_{fus}$	Fuselage total cross section area.
$A_{stringer}$	Area of the stringer.
C	Shear flexibility.
$C_D$	Coefficient of Drag.
D	Diameter.
$D_{camera}$	Camera's Drag Force.
$E_f$	Fastener Young's modulus.
$F_{bu}$	Bearing ultimate force.
$F_{xstringer}$	Stringer X force.

$F_X$	Skin X force.
$F_Y$	Skin Y force.
$K_x$	Shear stiffness in X.
$K_y$	Shear stiffness in Y.
$K_z$	Axial stiffness.
$K_{tg}$	Stress concentration factor based on the gross area.
$L_f$	Fastener Grip length.
$M_{bending}$	Bending moment at the installation area.
MS	Margin of safety.
MTOW	Maximum take off weight.
MZFW	Maximum zero fuel weight.
$n_{down_{ULT}}$	Ultimate vertical load factor down.
$n_{gust_{LIM+}}$	Maximum limit gust load factor.
$n_{gust_{LIM-}}$	Minimum limit gust load factor.
$n_{gust_{ULT+}}$	Ultimate maximum vertical gust load factor.
$n_{gust_{ULT}}$	Ultimate minimum vertical gust load factor.
$n_{max_{LIM}}$	Maximum limit load factor.
$n_{min_{LIM}}$	Minimum limit load factor.
$n_{up_{ULT}}$	Ultimate vertical load factor up.
$n_{maneuver_{LIM+}}$	Maximum limit maneuvering load factor.
Р	Cabin pressure.
$R_{max}$	Maximum fuselage outer radius.
$S_{max}$	Maximum shear force.
$t_{doubler}$	Thickness of the doubler.
$t_{skin}$	Thickness of the skin.
W	Fuselage weight.

# Glossary

3D	Three Dimensional.
AA	Antenna Aperture.
AES	Aircraft Earth Station.
AL	Aluminum.
APM	Aircraft Personality Module.
ARINC	Aeronautical Radio Incorporated.
ATG	Air-to-Ground.
CAA	Civil Aviation Authorities.
CAF	Classification Assessment and Application
	Form.
CCS	Certification Compliance Sheet.
CS	Certification Specification.
DLE	Drawing List Electrical.
DLM	Drawing List Mechanical.
DPS	Subcontractor Document Process Slip
DTA	Damage Tolerance Analysis.
EASA	European Union Aviation Safety Agency.
EIL	Electrical Item List.
FAA	Federal Aviation Administration.
FEM	Finite Element Method.
ICAO	International Civil Aviation Organization.
IF	Intermediate Frequency.
KANDU	Ka/Ku-band Aircraft Network Data Unit.
KRFU	Ka/Ku-band Radio Frequency Unit.
LC	Load Case.
MBPS	MegaBytes Per Second.
MDL	Master Data List.
MMPDS	Metallic Materials Properties Development and
	Standardization.
MODMAN	Modem and Manager.

OAE	Outside Antenna Equipment.
OEM	Original Equipment Manufacturer.
PRD	Project Description.
RF	Radio Frequency.
SATCOM	Satellite Communication.
SRM	Structural Repair Manual.
SSR	Structural Substantiation Report.
STA	Station.
STC	Supplemental Type Certificate.
тс	Type Certificate.
VM	Von Mises.

# **Chapter 1**

# Introduction

# 1.1 Evolution of the Aeronautical Industry

Aviation is one of the most broad industries that exists, since it provides a worldwide transportation network that facilitates a global business and people connection, while playing an important role in the economic growth of countries. Furthermore, air transportation is a major employer (about 29 million jobs globally) and a highly efficient user of resources and infrastructures. This market has continued to expand over the years, due to the increasing demand for passenger and freight services, the technological progress and the associated investment, having managed to recover from several crises and facing now a new one : COVID-19 [1]. Figure 1.1 depicts the aviation market trend from 1944 to 2018.



Figure 1.1: Aviation evolution from 1944 to 2018 (Revenue Passenger-Kilometers - darker line and Freight Tonne-Kilometers - lighter color line) [1].

By analyzing figure 1.1 it is concluded that the Revenue Passenger-Kilometers, which is the number of kilometers traveled by paying passengers, also known as airline traffic [2], has been growing exponentially since the 1940's, managing to overcome world crisis like terrorist attacks and wars. This growth has also been experienced by the Freight Tonne-Kilometers, also called freight traffic, which is the freight tones carried on a flight stage multiplied by the distance of the flight [3].

This growth generated a higher demand for different types of industry services such as aircraft modifications, more specifically changes/alterations. The two previous terms mean the same, although alteration is the term used by the FAA [4] and change is the term used by EASA [5]. These two civil aviation authorities will be presented in more detail in section 1.3.

## 1.2 Aircraft Modifications

#### 1.2.1 Alteration versus Repair

An aircraft modification can be divided into two parts : alteration and repair. The first part is depicted by the FAA as [4]: "...the modification of an aircraft from one sound state to another sound state; the aircraft meets the original airworthiness specifications and standards both before and after the modification". In other words, it is a change made to an aircraft, for example, its systems, engines or furnishings, where new equipment or features are added [5, 6]. More specifically, common alterations include antenna and camera installations on the fuselage, which will be presented throughout this thesis. The second part is described, as well by the FAA, as [4] "...the elimination of damage and/or process of restoration".

Furthermore, alterations and repairs can be classified into minor and major. A major alteration is defined as [4] : "...an alteration not listed in the aircraft, aircraft engine, or propeller specification-

- 1. That might appreciably affect weight, balance, structural strength, performance, powerplant operation, flight characteristics, or other qualities affecting airworthiness; or
- 2. That is not done according to accepted practices or cannot be done by elementary operations.

A minor alteration is simply [4] "...an alteration other than a major alteration". The definition of these terms has been controversial for many years, because there have been scenarios whether it is not clear how to classify the modification. The primary areas of controversy revolve around the meaning of "appreciably affect" and item number 2 from the definition of major alteration [4]. This means that every modification should be reviewed thoroughly so that the correct classification is given.

The definitions of major and minor repairs are not presented because they are out of the scope of this master thesis.

#### 1.2.2 Modification Certification

These different modifications need to be certified by the adequate Civil Aviation Authorities (CAA), unless the company has already the permission to approve the modification by their own office of airworthiness, under the privileges of 21J, which is the case of Jet Aviation for modifications classified as Minor.

In order to understand more on how the certification process works, it is important to define two terms. The first is the Type Certificate (TC), that is a document on which the authority states that a

type design (which can be an aircraft type, model, engine or propeller) is in compliance with all the applicable requirements. The TC is not an authorization for the operation of the aircraft, it simply freezes the product configuration and production methods. In order to have the permission for the operation of the aircraft, the airworthiness certificate must be obtained [7].

The second term is the Supplemental Type Certificate, which needs to be created when a product is altered by introducing a major alteration to it [7], and it is what Jet Aviation needs to apply for when doing one of these types of modifications.

On this master thesis only major alterations will be spoken of, and the important documents for the STC application will be presented in chapter 6. In order to understand more about this subject, the descriptions of the different CAA and the International Civil Aviation Organization (ICAO) are presented in section 1.3.

# **1.3 Civil Aviation Authorities**

The rapid growth in aviation led to the increased concern in terms of safety, which turned into a need of having a national authority that could help solving this issue. The Civil Aviation Authorities, which are institutions that were developed by several world countries, in order to guarantee flight safety, helped solving this problem. They have four main functions which are [7] : prescribing airworthiness requirements and procedures; informing the interested parties regarding the behind-mentioned prescriptions; controlling aeronautical material, design, manufacturing organizations and aircraft operators; certifying aeronautical material and organizations.

The CAA however, do not operate on its own but within a framework established by the International Civil Aviation Organization [8]. This agency came into existence on the 4<sup>th</sup> April 1947, having now more than 180 contracting states. Their aims are the achievement of standardization in the operation of a safe, regular and efficient air service, which has been fulfilled by creating 18 annexes called the International Standards and Recommended Practices. Furthermore, they also aim to develop the principles and techniques of international air navigation [7].

Besides ICAO there are two important entities which have a major role in aviation. In Europe, there is EASA, which represents the civil aviation regulatory authorities of a number of European states, who agreed to participate in this development of common safety regulatory standards and procedures. In the United States of America there is the FAA which represents all their states [7].

The regulatory agency that will certify the modifications presented in this thesis is EASA, since the country of origin of the aircraft, Azerbaijan, belongs to EASA's Pan-European Partners (PANEP). This is a community of non-EASA European countries which cooperate with EASA in order to implement the European Union aviation safety rules [9].

#### 1.4 Jet Aviation

Jet Aviation was founded in Basel, Switzerland, in 1967, when Carl W.Hirschmann bought the former Globe Air hangars. Having started as a maintenance company, it expanded over the years and it now provides services such as completions, refurbishment, fixed-base operator, aircraft charter and aircraft management or staffing. The Hirschman family built Jet Aviation from a small local maintenance operation into a global recognized leader in the business aviation industry.

Currently, Jet Aviation operates as an independent business unit within the General Dynamics Group, having around 40 centers spread out around the world and more than 5000 employees. The center of Basel has more than 1000 employees alone and a vast diversity of aircraft in maintenance and completions in its hangars.

The Jet Aviation center of Basel holds licenses for maintenance under the P145 regulations, production rights under Part 21G regulations and design organization privileges under Part 21J. The operations in this center are focused on private aircraft, that range from small Falcon and Gulfstream jets to larger aircraft such as the B747, B777 and B787 [10, 11].

# 1.5 Covid 19 Impacts on the Aeronautical Industry

In the beginning of 2020 the World was presented with a new virus strain: COVID-19. For the first time in the 21st century, humanity was struck with a severe pandemic that affected almost all society's fields. The aviation industry had to adapt, since less people were traveling due to the closure of borders and health concerns. Figure 1.2 depicts the effect of COVID-19 on commercial air transportation.



26-Dec 13-Jan 31-Jan 18-Feb 7-Mar 25-Mar 12-Apr 30-Apr 18-May 5-Jun 23-Jun 11-Jul 29-Jul 16-Aug 3-Sep 21-Sep 9-Oct 27-Oct 14-Nov

Figure 1.2: COVID 19 effect on commercial air travel from January - November 2019 vs 2020 [12].

By inspection of figure 1.2 it is concluded that there was a high reduction of flights around March 2020 (start of the pandemic). Overall, the commercial flights number increased as the months passed,

however they stopped growing from August onward, having been less 39.8% of commercial flights in November when compared to 2019 [12]. It is estimated that this pandemic resulted in an overall reduction of 2.891 to 2.893 million passengers and a loss of approximately 391 billion United States Dollars [13].

In a business perspective there was the need to come up with new ideas and strategies, so that the economic crisis did not make some companies disappear. In order to minimize the effects of the pandemic in Jet Aviation, it was adopted the reduction of working hours, allowing thus the company to save money.

# 1.6 Objectives

The overall aim of this thesis is to study different types of structural fuselage major modifications, which can be broken down into specific objectives like :

- · Investigate the current solutions for internet access on an aircraft;
- · Understand how standardized equipment can be used in major structural modifications;
- Learn what should be done in order to start a modification, such as the determination of the system's location and environment definition;
- · Show how the structural installation of a Ka-band antenna and a quad camera are done;
- Analyze different design concepts in a quad camera installation, based on the static loading conditions, installation weight and cost;
- · Explain how the certification process works and what documents are needed for it.

# 1.7 Thesis Outline

The contents of this thesis are organized by chapters which are :

#### Chapter 2

An overview of the wireless internet connection methods in an aircraft is done, as well as a comparison between the different frequencies used for it. The Aeronautical Radio Incorporated (ARINC) 791 standard, as well as its importance in the industry, is presented. Finally the subject of fuselage cut-outs is described, since it is related to the design guidelines used in Jet Aviation.

#### Chapter 3

The installation of a Ka-band antenna system is described, starting by investigating the parameters that influence its location, as well as researching the aircraft's environment in order to have a more accurate design. The structural designed components are explained, some based on the ARINC standard and some based on the load transfer philosophy.

#### Chapter 4

The installation of a quad camera is presented by using the same initial strategy, which is defining its position and aircraft's environment in that region. The FEM model of this installation is done in order to conduct the static stress analysis.

#### Chapter 5

Three quad camera design variations are tested, in order to improve the company's solution in terms of weight and cost, while keeping good results of static stress analysis. The conclusion of whether or not to invest in a new design is given.

#### Chapter 6

The certification and compliance documents needed for the STC application are presented and defined.

#### Chapter 7

The thesis conclusions are presented and future developments proposed.

# Chapter 2

# Aircraft Telecommunication Systems and Design Standards

In the past, the aeronautical communications market was limited to operational communications between cockpits and control towers. The market's demand, as well as the technological improvements enabled the expansion and integration of data communications for passengers [14].

This chapter presents the different ways to integrate private communications in an aircraft environment. The standard used by Jet Aviation for the Ka-band system is explained, as a way of introducing these types of installations. Finally, an overview of fuselage cut-outs is done, in order to justify some of the used design guidelines.

# 2.1 Demand and Offer

Like seen in section 1.1, the demand for air transportation has been growing exponentially since 1944. With this growth there was also the demand to make air travel more pleasant and productive for passengers, which was conquered by using wireless-in-cabin communication and multimedia data networks [15].

In 2003 airplanes were described as being [15] "...the last remaining islands where mobile communications and internet access are not available" and, by fast forwarding 17 years, it is possible to observe that the use of these wireless communication technologies is still very limited, due to the high costs that these systems have. That is why commercial airlines do not normally invest on this technology, being them usually most required by private costumers.

In fact, inflight WI-FI is a relatively recent development since Boeing only entered this part of the business in 2001, Airbus in 2005 and Gogo in 2008 [16].

# 2.2 Airplane Internet Wireless Connection

Wireless internet access on board can be achieved in two ways : Air-To-Ground (ATG) or Satellite Communication (SATCOM). In general the ATG antennas are located on the bottom of the aircraft and the satellite communication systems are located on top of it. An example of this can be seen in figure 2.1.



Figure 2.1: WI-FI connection on an aircraft [16].

## 2.2.1 ATG

The ATG is a ground based communication system that uses mobile broadband towers which transmit, route and receive data to and from the aircraft. An ATG system is composed of three main components [17] :

- · Land based network infrastructure;
- Aircraft antenna technology : Equipment mounted on the aircraft's lower fuselage that receives and transmits data to and from other parts of the network infrastructure. They are designed to connect to the nearest tower in their range;
- In-cabin WI-FI network : Routers, servers, wireless antennas and personal devices.

These types of systems have drawbacks, like service disruption if the vehicle is passing over large bodies of water or particularly remote terrain (since there are no ground towers in these locations), and slow internet speeds (3-10 MegaBytes per second (MBps) per aircraft) [14]. In figure 2.2 the connection concept of these systems is presented.



Figure 2.2: ATG connection on an aircraft [18].

This type of WI-FI connection system also has its advantages, like being less expensive, when compared to the SATCOM system, because of the lower equipment and maintenance costs. Furthermore, since the distance between the towers and the aircraft is lower than the distance between a satellite and the aircraft, then the latency (network delay) is also lower on the ATG [14].

## 2.2.2 Satellite Communication

An alternative to the ATG system is the SATCOM system, which can be seen in figure 2.3.



Figure 2.3: SATCOM system connection on an aircraft [19].

The Aircraft Earth Station (AES) connects to the Ground Earth Station with the aid of a satellite. The AES function is to transmit, receive and process signals, through a mounted antenna on top of the fuselage or on the tail, thus providing communication services like WI-FI [19]. The SATCOM system has a wider coverage, when compared to the ATG, since it can also provide connection over the ocean and in deserted land. This is possible because, as the aircraft moves along its route it automatically connects to the closest satellite in orbit, maintaining then the internet connection on board. Regarding internet speeds the evolution is also significant, having now the ability to provide as much as 70 MBps to the aircraft, depending on the system and frequencies used [14, 20].

Despite all of its advantages, these types of systems have a higher latency, since the signal needs to travel up to space in order to reach the satellite. This latency depends on the type of satellite orbit, meaning that a Geostationary Orbit (GEO) will result in a higher latency than a Low Earth Orbit (LEO). Furthermore it is an expensive system, when compared to the ATG, due to the high equipment and maintenance/repair costs [14].

# 2.3 Satellite Communication Frequency Bands

The Earth's atmosphere absorbs several regions of the electromagnetic spectrum. In fact, the only non absorbed parts are the visible light and part of the radio spectrum. Due to this reason, the most common satellite frequencies belong to the latter and can be seen in figure 2.4 [21, 22].



Figure 2.4: Satellite frequency spectrum [22].

Satellites are projected to use a specific frequency domain based on its end use. For example, the X-band is used for military purposes while the Ka-band is used for general communication [22]. This thesis will only focus on three frequency domains being them the K, Ku and Ka bands.

#### 2.3.1 K-Band

The K-band is the band with frequencies between 18 and 26 GHz [22]. In order to determine its benefits several experiments were done, during the Second World War, on devices that used the North Atlantic Treaty Organization (NATO) K-band frequencies (20-40 GHz). This resulted in the conclusion that water

vapor in the atmosphere absorbs large portions of electromagnetic radiation, around the 22.3 GHz frequency thus not being suitable for long range applications, as it can be seen in figure 2.5 [23].



Figure 2.5: Atmospheric water vapor influence on different frequency bands [23].

It is used, for example, in short range radars or astronomical observations, not being suitable for long range satellite communication. For those types of applications it is better to use frequencies such as the Ka-band and Ku-band [24].

#### 2.3.2 Ka-Band

The Ka-band, which stands for "K above", meaning frequencies higher than the K-band, ranges between 26-40 GHz [22]. This frequency band allows for higher bandwidths thus granting better data flow in the system, which is one of the reasons why it is normally used for communication satellites and high-resolution, close-range, targeting radars on military aircraft [22].

According to the National Aeronautics and Space Administration (NASA), there is a need for higher frequency bands use, because the demand for communication in present days is placing strains on the available bandwidths of lower frequency bands [25].

Nowadays there are a large number of Ka-band working satellites owned by different companies such as Intelsat and Inmarsat, which means that the coverage of these communication systems might vary from provider to provider. The Inmarsats' Global Xpress coverage, presented in figure 2.6, depicts a global communication system covering both land and ocean.



Figure 2.6: InmarSats' Ka-band satellite constellation coverage [26].

Even though it seems that higher frequencies such as the Ka-band is the way to go, it is important to keep in mind that they also suffer more attenuation due to rain than lower frequencies (figure 2.7). Nonetheless its use still shows promising results, bringing better communication rates and connection speeds to the aircraft.

#### 2.3.3 Ku-Band

The Ku-band stands for "K under", which represents the band with frequencies lower than the K-band. It ranges from 12-18 GHz and is used in satellite communication and direct broadcast satellites [22].

Its origin dates back to the 1980's, when the C-band (4-8 GHz) was still heavily used in the commercial satellite communication field. In order to use the C-band there needed to be a reduction in satellite transmissions power, in order to avoid interference with terrestrial microwave systems, which does not happen when using the Ku-band domain [27].

The comparison between these three different frequencies (Ku, K and Ka) on four different parameters can be seen in figure 2.7, which sums up what has been said before.



Figure 2.7: Frequency's influence on four important parameters [28].

# 2.4 ARINC 791 Standard

As seen from figure 2.3, one of the components of the SATCOM system is the Aircraft Earth Station. Jet Aviation uses, as the AES, the ARINC 791 standard which sets the desired characteristics of the Ka/Ku-band SATCOM system intended to be installed on the aircraft depicted throughout this thesis.

On figure 2.8 the Ka/Ku-band system is depicted as a block diagram, as explained in the Honeywell's JetWave manual [29], which can be used to describe the overall SATCOM system and its subcomponents, which are the same as in the ARINC 791 standard. The most relevant components of the AES are presented and described, so a better insight to this system is obtained.



Figure 2.8: Ka/Ku-band system breakdown [29].

#### 2.4.1 Outside Antenna Equipment (OAE)

The OAE consists of an antenna aperture (AA), a low noise amplifier, a polarization control unit (Ku only), an antenna positioner, an adapter plate, a radome and a skirt or fairing [19]. The typical OAE with Ka/Ku-band Radio Frequency (RF) interfaces can be seen in figure 2.9. The most relevant components of the OAE will be described next.



Figure 2.9: Typical OAE with Ka/Ku-band RF Interfaces [19].

#### 2.4.1.1 Antenna Aperture

The antenna aperture is a high gain radiating structure that has the ability to receive and transmit Ka/Kuband radio frequency signals [19]. There are two types of antenna apertures, depending on the zone of the aircraft where it is going to be installed. If the antenna is installed on the tail then it is a Tail Mounted Antenna (TMA) and if it is installed on the fuselage it is a Fuselage Mounted Antenna (FMA). Both of these solutions can be seen in figure 2.10.



(a) Fuselage Mounted Antenna



(b) Tail Mounted Antenna



#### 2.4.1.2 Radome

The radome is used in order to protect the OAE from environmental agents such as water, air flow, electrical discharges and birds, which might damage the system in critical ways [19].

#### 2.4.1.3 Adapter Plate

The adapter plate provides the mechanical interface between the antenna subsystems, including the radome and skirt, and the aircraft via seven fittings. This structure is designed to withstand the loads that the radome, skirt and antenna impose on the aircraft [19].

#### 2.4.1.4 Skirt

The skirt provides an interface between the radome and a specific aircraft fuselage, meaning that this component is aircraft specific, due to the outer radius of the aircraft's fuselage [19].

The ARINC'S 791 components of the OAE can be seen in figure 3.13.

## 2.4.2 Ka/Ku Band Radio Frequency Unit (KRFU)

The KRFU is the converter between radio frequency and Intermediary Frequency (IF) signals. It downconverts the Ka/Ku-band RF signal to an IF usable by the Modem and Manager (MODMAN) and it up-converts the MODMAN'S IF signal to a Ka/Ku-band RF signal usable by the antenna. It also power amplifies the Ka/Ku-band signals in the up-conversion [19]. The KRFU can be see in figure 2.11.



Figure 2.11: Honeywell's JetWave KRFU unit [30].

## 2.4.3 Ka/Ku Band Aircraft Network Data Unit (KANDU)

The KANDU is responsible for several functions such as: the provision of power to the antenna subsystem; the Ethernet interface between the KRFU, OAE and the MODMAN; the transmit enable/disable ability; the KRFU control and management; the antenna subsystem control and monitoring and the stabilization and tracking [19]. This unit is presented in figure 2.12.



Figure 2.12: Honeywell's JetWave KANDU unit [30].

#### 2.4.4 MODMAN

MODMAN is the name of the unit composed by the Modem and the Manager which will be described separately.

The Modem includes a modulator and a demodulator. The first one takes baseband data from the aircraft and superimposes it on a RF carrier suitable for transmissions using the antenna subsystem. The demodulator does the opposite, it takes the IF signal received from the antenna's subsystem and converts it to baseband data. Additionally, the modem will provide real-time information to the antenna subsystem, including synchronization lock status and signal strength [19].

The manager configures and commands all system components and provides an interface between the antenna subsystem and the aircraft systems [19]. The MODMAN is presented in figure 2.13.



Figure 2.13: Honeywell's JetWave MODMAN unit [30].

#### 2.4.5 Aircraft Personality Module (APM)

The APM retains Ka/Ku-band Satcom system configuration information that may be specific to each installation. This unit will ease the process of changing the MODMAN since it will save the installation calibration parameters and other installation specific information [19]. The drawing of the APM is presented in figure 2.14.



Figure 2.14: Honeywell's JetWave APM unit [29].
#### 2.4.6 ARINC 791 Advantages [19]

This standard has several advantages which translate into the interchangeability at a number of different levels such as:

- Aircraft Manufacturer and Type Interchangeability : the same equipment can be fitted to several aircraft types built by different aircraft manufacturers such as Boeing and Airbus;
- Equipment Manufacturer Interchangeability : equipment from different manufacturers can be used in this standard, thus protecting the company in case there is a supply problem;
- Frequency Band Interchangeability : the same aircraft provisions can be used for either Ku-band or Ka-band equipment, which allows more flexibility to the client in case they desire to change the frequency domain in the future, since they do not need to do another fuselage major modification;
- Satellite System Interchangeability : the same Ka/Ku-band antenna subsystem (OAE, KRFU and KANDU) can be used for different Ka/Ku-band satellite systems. This means that, in the future, an airline or costumer could change their satellite provider and still be able to use their antenna subsystem, although they would need a new MODMAN;
- Antenna Subsystem and Modman Interchangeability : this allows the ability to source the antenna's subsystem from one supplier and the MODMAN from another, as a direct consequence of the satellite system interchangeability depicted above;
- MODMAN and APM interchangeability : the MODMAN and APM are a functional doublet which means that, if one unit fails it can be replaced independently without having to replace the other as well. They are, however, manufacturer-specific units due to unique electrical signaling and protocol implementations.

The ARINC 791 standard was used in the installation of the Ka-Band system on the B777-200LR, and so the initial design concepts were based on its manual [19]. In order to have a better understanding of the design decisions made throughout this thesis, one other topic will be presented which are fuselage cut-outs. This will give an overlook of what is used in order to strengthen the skin after a hole is drilled on it, as well as give a brief look on what shape cut-outs should have. Additionally, the most important design guidelines that are used, such as the spacing between rivets (pitch), will be explained.

## 2.5 Fuselage Cut-Outs

When a fuselage cut-out is made it should be reinforced with a doubler (sheet metal part) in order to carry the load which would have been carried out in the cut-out panel, as well as the forces due to the redistribution of that load [31]. This is viewed with disfavor, since the reinforcement results in an increased cost and weight to the overall design that is being made [32].

#### 2.5.1 Cut-Out Shape

An important factor, when doing a cut-out, is deciding which shape the hole should have. This choice will be based on stress concentrations, which refers to the localized high stresses that occur at a geometric discontinuity. They are measured by using the stress concentration factor, K, which is defined as the ratio of the peak stress to a reference stress [33]. This concentration of stresses depend on the shape of the hole that is drilled, as seen in figure 2.15.



Figure 2.15: Stress concentration factors for different elliptical holes in a biaxially stressed panel [33].

In figure 2.15 the variable  $K_{tg}$  is the stress concentration factor for which the reference stress is based on the gross cross-sectional area (far from the hole) [33]. In order to compare the different shapes, three load cases were tested, with the values of  $\frac{\sigma_2}{\sigma_1} = 0.5$ ; 1; 2, for three values of a and b being them a = 2b, a = b and b = 2a. The values of  $K_{tA}$  ( $K_{tg}$  in point A) and  $K_{tB}$  ( $K_{tg}$  in point B) will be determined by using the equations from figure 2.15. The results are presented in table 2.1. It is worthy of note that a = b represents a circle, a = 2b represents an ellipse aligned with  $\sigma_2$  and b = 2a represents an ellipse aligned with  $\sigma_1$ .

	a = 2b		a	a = b		b = 2a	
	$K_{tA}$	$K_{tB}$	$K_{tA}$	$K_{tB}$	$K_{tA}$	$K_{tB}$	
$\frac{\sigma_2}{\sigma_1} = 0.5$	4.5	0	2.5	0.5	1.5	1.5	
$\frac{\sigma_2}{\sigma_1} = 1$	4	1	2	2	1	4	
$\frac{\sigma_2}{\sigma_1} = 2$	3	3	1	5	0	9	

Table 2.1: Stress concentrations at A and B for different cut-out shapes and loading conditions.

By looking at the results it is possible to see that the ellipse with a = 2b has lower stress concentrations if the higher load is aligned with its shape, which is when  $\frac{\sigma_2}{\sigma_1} = 2$ . A similar result is observed when b = 2a since now the ellipse is aligned with  $\sigma_1$  and it is when  $\frac{\sigma_2}{\sigma_1} = 0.5$  that the stress concentrations are the lowest. The circular case has an equilibrium of stress concentrations, having lower stresses when the loads are the same in both directions.

To sum up, the elliptical cut-out shapes are only a good solution when the direction of higher stresses is known. In an aircraft, the direction of the maximum stress is not always aligned with a single direction and can change according to the load case, which would mean that the elliptical shape would not be suitable. The shape that is able to have the most balanced behavior, regardless of the direction of the loads is then the circular shape.

#### 2.5.2 Open Holes versus Plugged Holes

There is a difference, in terms of stress concentrations, between the holes made for fasteners (which are occupied) and the holes made for cable feed through (which are unused holes). In figure 2.16 it is possible to see the relation between the types of hole filling and the stress concentrations and relative structural life of the component that has the hole.



Figure 2.16: Stress concentrations around unused and used holes [32].

Open holes lead to higher stress concentrations than the holes that have a rivet in it, since the latter will create a compression field around the hole thus reducing the stress concentrations [34]. This is why the unused holes are more critical to the aircraft's structure, and should be analyzed thoroughly.

#### 2.5.3 Design Guidelines

The design of a structural modification includes, inevitably, the use of rivets and its distribution. In order to have a safe design there are certain rules that should be followed, starting with the choice of inter-rivet spacing (pitch).

#### 2.5.3.1 Fastener's Pitch

When designing a structural joint the used fastener pitch is of great importance, to ensure compliance with the fatigue requirements and ultimate loads to which the structural joint is concerned. The effect of the fastener's pitch in the stress concentrations, for 2 adjacent holes, can be seen in figure 2.17.



Figure 2.17: Stress concentration factors for a tension case of an infinite panel with two circular holes [33].

When the pitch is equal to 4D (D is the fastener's diameter), the stress concentrations keep unchanged. This happens since the distance is large enough so that the holes are barely interacting with each other, keeping then the stress concentrations constant. A lower rivet's pitch will mean higher stress concentrations, which would result in a lower number of fatigue life cycles for the part [31]. Additionally, the lower the pitch the harder will be to do a repair, because when a rivet is removed there is the probability of needing to use an oversize repair fastener, because of the deformed hole. With the use of the oversize fastener, the effective fastener pitch is reduced and the stress fields around the fastener holes start interacting more with each other which is not desirable.

Regarding the maximum rivet pitch, this should be between 6D-8D in order to prevent failure due to inter-rivet buckling (figure 2.18) [32]. Even though the upper limit is 8D, in Jet Aviation it is a common rule to have 6D as the maximum pitch in order to avoid having very large parts.



Figure 2.18: Inter-rivet buckling [32].

To sum up, the rule in Jet Aviation, when designing the fasteners pattern, is always keeping the pitch between 4D-6D, due to all the discussed factors.

#### 2.5.3.2 Edge Margin

The edge margin is the distance between the center of the rivet and the edge of the plate where it is being placed. This margin needs to be at least 2D according to static and fatigue requirements [32] however, in Jet Aviation, all edge margins are considered to be 2D + 1 mm in order to take into consideration the oversize of the rivets, when a repair is being made.

#### 2.5.3.3 Radius Clearance

The radius clearance is the distance that the center of the rivet should have from a specific radial component. This is used in order to guarantee that the rivet head will fit entirely on a flat surface, without being in clash with the radius. This clearance is taken as D+1 mm, since the head of the rivet has a dimension approximately between 1.25D-1.66D [35]. The fact that an extra 1 mm is given is, again, related to a possible oversize that can be done in the future. This way the new rivet will still fit where the old was previously placed.

## **Chapter 3**

# Ka-band Antenna Structural System Design

The Ka-band antenna installation is a major alteration which requires a thorough investigation of the soon-to-be modified aircraft and engineering knowledge. In this chapter, the modeling of the aircraft's environment (primary structure) will be shown, as well as the techniques used to improve its accuracy. Furthermore, the external and internal structural design of the Ka-band system, for the Boeing 777-200LR, will be presented and justified.

## 3.1 Antenna Installation Position

One of the first things that is done when a Ka-band system needs to be installed on an aircraft is to determine its position. There are several factors that need to be taken into consideration when positioning the antenna, which will be presented next.

#### 3.1.1 Aerodynamic Considerations

The aerodynamic loads applied on an aircraft have a great influence on the fuel consumption and overall performance of the vehicle. In general, an aircraft's fuselage can be divided into two sections, when it comes to the aerodynamic domain. The first is called the critical aerodynamic area and goes from the nose of the aircraft until the middle of the wings. This area is more sensitive to flow perturbations since they can change the flow conditions reaching the wings, which may have a significant impact on the aircraft's performance. The second area is the non critical aerodynamic area and includes the region from the middle of the wings until the end of the fuselage [36]. Both of these areas are represented in figure 3.1.



Figure 3.1: Aerodynamic sections of a Boeing 777-200LR [36].

It is then clear that the most suitable and preferable area to install the antenna is the non critical aerodynamic area. Additionally, the antenna should be installed in the vertical plane of symmetry of the aircraft, to avoid asymmetric flow perturbations, which means that the system would be taking different loads in regards to its local symmetry plane.

#### 3.1.2 Fuselage Bending Moment

The bending moment increases along the fuselage having its maximum at the wingbox and then decreasing until the tail. The bending moment plot for the aircraft in question can be seen in figure 4.9, on which it can be observed the areas with the highest and lowest bending moments. Based on the above mentioned, it is structurally preferred not to perform modifications on the central fuselage. It is also likely that that would decrease the lifespan and reduce the inspection intervals of the antenna, since the installation is suffering a higher bending load.

#### 3.1.3 Aircraft External Equipment

While defining the position of an antenna it must be taken into consideration the position of the already existing external equipment, due to the electromagnetic, structural and aerodynamic interferences.

In Appendix A.1 the B777-200LR layout is presented, with the existing external equipment such as the different Very High Frequency (VHF) antennas and lights. It is important that the SATCOM system is not in clash with any of the already existing items, and is at least one frame bay away from them, due to the aerodynamic interferences. Note that the radome should be the guide for this clash check since it is the largest part of the external system. In terms of the electromagnetic interference, it is important to see the type of systems that will be around the antenna, in order to guarantee that they don't transmit in

the same frequency band as the Ka-band system, since this will result in interference if the systems are close enough.

#### 3.1.4 Aircraft Internal Equipment

Since the installation also has an internal part it is then critical to check the interior of the aircraft, in order to guarantee that there are no clashes with already existing components. In case there is an interference between the new installation and the aircraft, then a decision has to be made to either relocate the existing aircraft component or define a new location for the antenna.

#### 3.1.5 Illumination Obstruction

Another aspect to take into consideration is the position of the antenna in regards to the beacon light. This equipment has the objective of improving the aircraft's visibility while on air or on ground, to others, having an allowable obstruction which is quantified by the Certification Specification (CS) 25 Amendment 22 Section 25.1401 - Anti-collision light systems [37]. This amendment states that :

"...(b) Field of coverage. The system must consist of enough light to illuminate the vital areas around the aeroplane considering the physical configuration and flight characteristics of the aeroplane. The field of coverage must extend in each direction within at least 75<sup>o</sup> above and 75<sup>o</sup> below the horizontal plane of the aeroplane, except that a solid angle or angles of obstructed visibility totalling not more than 0.03 steradians is allowable within a solid angle equal to 0.15 steradians centred about the longitudinal axis in the rearward direction."

In order to check if the installation fulfills this requirement, firstly the location of the beacon light needs to be known. By analyzing the illustrated parts catalogue of the aircraft it was found that the beacon light was located at Station (STA) 876 (the aircraft frame stations are numbered, as seen in Appendix A.1). The preliminary antenna location, that was used to test the beacon light interference, was STA 1455 - STA 1546.5, since it fulfills the described requirements up to this point. In figure 3.2 the position of the beacon light, as well as the Ka-band system are represented.



Figure 3.2: Beacon light obstruction on the B777-200LR.

The green lines represent the existing beacon light's interference caused by the tail of the aircraft. If the antenna was inside those boundaries then it would be within the existing blockage and thus no additional obstruction would be caused by it. The analysis that addresses the antenna's additional obstruction, in relation to the maximum allowable per the regulations, will be presented next.

It was geometrically determined that the point with the biggest obstruction, in the antenna, was 30 inches aft of the most forward station (STA 1455). This means that the distance from the beacon light to that point is r = 1455 + 30 - 876 = 609 in = 15.469 m.

This distance will be used when calculating the obstruction boundaries. In order to do that, the concept of steradian should be explained. It is a dimensionless unit used in three dimensional geometry to determine the amount of field of view, from some particular point, that a given object covers [38, 39]. One steradian, as shown in figure 3.3, is equal to the solid angle subtended at the center of a sphere, whose area equals the square of the sphere's radius ( $r^2$ ).



Figure 3.3: Section of cone (1) and spherical cap (2) that subtend a solid angle of one steradian inside a sphere [40].

Furthermore, the area of a spherical cap can be calculated by using equation 3.1, as demonstrated in [41], and by using the variables from figure 3.3 :

$$A = 2\pi rh\,,\tag{3.1}$$

where r is the sphere's radius and h is the height of the spherical cap. With this formula the radius of the different obstruction boundaries,  $r_o$ , can be calculated. In these calculations, the radius of the sphere, r, will be the distance from the beacon light to the point with the maximum obstruction of the antenna.

Firstly, the areas of the obstruction boundaries, according to CS 25.1401, were calculated and came as :

- $0.15sr = 0.15 \times r^2 = 0.15 \times 15.469^2 = 35.8935 m^2$  (Obstruction boundary)
- $0.03sr = 0.03 \times r^2 = 0.03 \times 15.469^2 = 7.1787 m^2$  (Allowable obstruction boundary)

In order to calculate the actual radius of the obstruction boundaries, equations 3.2a, 3.2b and 3.2c

were used. For the Obstruction Boundary it came that :

$$h = \frac{A}{2\pi r} = \frac{35.8935}{2\pi \times 15.469} = 0.3693 \ m \,, \tag{3.2a}$$

$$r - h = 15.469 - 0.3693 = 15.0997 m$$
, (3.2b)

$$r_o = \sqrt{(15.469)^2 - (15.0997)^2} = 3.3599 \ m$$
, (3.2c)

For the Allowable Obstruction Boundary the same method was applied, and by using equations 3.2a, 3.2b and 3.2c it came that  $r_o = 1.5098 m$ . The representation of these two boundaries is made in figure 3.4.



Figure 3.4: Beacon light obstruction boundaries on the B777-200LR.

Taking into consideration that the ARINC 791 system provisions are fully contained inside the allowable obstruction boundary then it is possible to conclude that any obstruction caused by this system is within the acceptable limits set by CS 25.1401.

By taking all the previous items into consideration it was concluded that the installation would be placed between STA 1455 and STA 1546.5 since it fulfills all the necessary requirements.

## 3.2 Aircraft's Environment Modeling

There are several environment modeling techniques and all should be used simultaneously, in order to assure a precise design. In fact, a detailed Three Dimensional (3D) model of the airframe is often not available, therefore alternative techniques must be used for environment definition, in order to guarantee that it is reproduced with the utmost reliability. The tools used will be presented next.

#### 3.2.1 Environment Research Tools

#### 3.2.1.1 3D Scanning

Reverse engineering (RE) is a process used to measure, analyze and reconstruct an already existent object. This technique can be described as "...a road map leading to reconstruction and reproduction" [42].

One of the tools used in RE is 3D scanning, which was used to replicate the installation area of the aircraft. To do this, a Handyscan 3D from the company Creaform was used which is depicted in figure 3.5.



Figure 3.5: Handyscan 3D machine [43].

The first step of the scanning is the placement of targets, which are small black and white stickers, on the object, which the machine will then use to reconstruct the object's geometry. In order for the scan to work successfully it needs to read three targets simultaneously, in a triangular pattern.

In this case, this technique was used to recreate the aircraft's environment such as its frames and stringers and the result can be seen in figure 3.8.

#### 3.2.1.2 Boeing Drawings

In order to recreate the frames, stringers, and the remaining components of interest, the drawings and 3D PDF's supplied by Boeing needed to be consulted. Figure 3.9 represents one of the ways in which Boeing's information can be used, in order to ease the model construction.

#### 3.2.1.3 Structural Repair Manual (SRM)

The SRM of the B777-200 (which includes the LR variation) has important information regarding the aircraft's environment such as the skin panel layout (figure 3.7), the fuselage radius information, the list of parts concerning the main structure and pre-approved typical repairs.

With these three tools it was possible to build a CATIA [44] model that included aircraft parts such as its skin, stringers, frames, shear ties and stabilizers which will be of great importance when designing the structural installation. The final environment result can be seen in figure 3.6.



Figure 3.6: B777-200LR primary structure in CATIA V5.

To achieve this, a detailed research was done and will be presented next, as well as the description and function of each structural component.

#### 3.2.2 Environment Modeling

#### 3.2.2.1 Skin

The aircraft's skin covers all fuselage and carries cabin pressure (tension) and shear loads [45]. This component is made of several skin panels which are optimized in terms of weight. As a result they are not all produced with the same thickness and can also have pockets inside of them (area where the thickness changes). The skin panel scheme for the Ka-band installation area can be seen in figure 3.7, where the numbers on the panels represent their thicknesses in inches.



Figure 3.7: Skin panels between STA 1455 and STA 1546.5 for the B777-200LR [36].

By analyzing figure 3.7 it is possible to conclude that the overall thickness of the skin is 0.09 inches except between stringers 1L-1R and frames 1476-1497 where thickness is 0.160 inches, and between frames 1455-1476 and stringers 5L-5R, where there are pockets with two thicknesses which are 0.09 and 0.1 inches. This means that there needs to be special attention when installing a provision on these areas, since it should be installed onto a single thickness. The skin pockets are not modeled in CATIA but can clearly be seen in the 3D scan presented in figure 3.8.



Figure 3.8: 3D scan made on the interior part of the aircraft.

Furthermore, another important parameter to take into consideration when designing the skin is its curvature. By analyzing the SRM of the Boeing 777-200 [36] it was found that the radius of the B777-200LR is 122 inches which is equal to 3098.8 mm.

#### 3.2.2.2 Stringers

The stringers are made to carry the longitudinal tension and compression loads [45]. In this aircraft they have a Z cross section, although their dimensions could not be perfectly determined due to the inaccessibility to the stringer's shape drawing. Nonetheless, for the external and internal installation the only important detail is the stringer holes position, which was available in a Boeing PDF, since this will influence the design. In figure 3.9 the stringer's cross sections are presented.



Figure 3.9: Typical stringer cross section of the B777-200LR [46].

#### 3.2.2.3 Frames

The frames help to maintain the fuselage's cross section shape and redistribute loads into the skin [45]. Just like the skin, they are also optimized in terms of weight which means they are machined with pockets of different thicknesses. It is important to know the exact location of the thickness changes, so that the structure that is being designed is not in clash with these pockets. In order to facilitate the modeling process, the PDF of the frames was extracted and placed on the modeled 3D frames, in order to avoid the replication of these pockets in 3D. The final result can be seen in figure 3.10.



Figure 3.10: Modeled frame with the pockets taken from Boeing's PDF.

As seen in figure 3.10 there is not a thickness uniformity in the frame, reason to why it is important to have special attention when connecting something onto the frames.

#### 3.2.2.4 Shear Ties and Stabilizers

The shear ties make the connection between the skin and the frames whereas the stabilizers connect the stringers and the frames, both with the objective of helping to distribute the loads between components. On figure 3.11 and 3.12 the shear clips and stabilizers are shown, respectively.



Figure 3.11: Shear clips connecting the skin and frames together.



Figure 3.12: Stabilizers connecting the stringers and frames together.

## 3.3 Installation Breakdown

The first step for a successful design is understanding the installation, since it will make the design an easier process. For that, the complete antenna's installation methodology is presented in figure 3.13 where it shows all the components that were used in this installation.



Figure 3.13: Exploded view of the Ka-band antenna installation [47].

The installation was divided into two parts : external and internal, which will be presented in the next sections.

#### 3.3.1 External Structural Installation

The external installation is composed of seven fittings, doublers and gussets (even though they are inside the aircraft they were projected at the same time as the other external components, hence why they are included in this group) and two feedthroughs.

#### 3.3.1.1 Fittings

The fittings are an assembly made of a machined part of Aluminum (AL) alloy 7050-T7451 and a bearing used for the connection to the adapter plate. The coordinates for the attachment points of the fittings are given in the ARINC 791, which means that those positions are already pre-determined and were the beginning of the design. In figure 3.14 all seven fittings are represented in their own reference system, independently of the aircraft references.



Figure 3.14: Fittings layout according to ARINC 791 [19].

It is important to note that YZ is the vertical plane orthogonal to the flight direction, XZ is the vertical plane along the flight direction and YX is the horizontal plane at a minimum gap of 8 mm above the top of the fuselage. In table 3.1 the coordinates for the center of the fitting's bearings are presented, taking into account the reference system from figure 3.14.

Fitting no <sup>⁰</sup>	Interface X [mm]	Interface Y [mm]	Interface Z [mm]
1	-635	-185.5	16.8
2	-635	203	15.8
3	0	-392.5	-1.4
4	0	392.5	-1.4
5	635	-187.5	16.7
6	635	187.5	16.7
7	1270	0	28

Table 3.1: Fitting's bearings center coordinates according to ARINC 791 [19].

The X coordinates are in bold due to the fact that those values can vary since the adapter plate allows some freedom of movement in X, as represented in figure 3.15.



Figure 3.15: Adapter plate's attachments.

The red rectangles in figure 3.15 highlight the attachments from the adapter plate, which control the male fittings. It is possible to see that in that region there are several holes, meaning that the male fittings can move, in X, therefore allowing the female fittings (installed on the aircraft) to move as well. This is why the X coordinates in table 3.1 are only representative, and may vary when the final design is made (which happened in this design). The adapter plate is made like this in order to allow its use on different aircraft, since the frame spacing varies from model to model.

Furthermore, the fittings are not all loaded in the same directions. In table 3.2 the loading directions for each fitting, according to ARINC 791, are presented.

Fitting no <sup>o</sup>	Loading direction	
1	Y,Z	
2	Z	
3	X,Z	
4	X,Z	
5	Y,Z	
6	Z	
7	Z	

Table 3.2: Fitting's loading directions according to ARINC 791 [19].

After having the attachment points determined, the fittings are extruded vertically until the skin is reached. The thicknesses of all fittings are based on past designs, since it allows for the vibrations of the antenna to be withstood successfully by them. The base's shape is based on the design rules, according to the fastener positions.

The final fittings shapes can be observed in figure 3.16



Figure 3.16: Fittings isometric view.

#### 3.3.1.2 Gussets

The gussets are machined parts made of AL alloy 7075-T651 that are used to transfer the loads from the fittings to the intercostals. The positions of the fitting's fasteners will influence the design of the gussets, since they attach to them. On fitting seven there is a different concept of gusset, since a single intercostal was used, which created a need to adapt the design (explained in section 3.3.2). In this case two half gussets were used, as it can be seen in figure 3.17.



Figure 3.17: Gussets isometric view.

#### 3.3.1.3 Doublers

The doublers are thin sheet metal parts made of AL alloy 2024 T3 that are used in order to strengthen the skin, due to the drilling of the fitting's attachment holes. They also help to distribute the shear load that would be concentrated on the fitting's fasteners.

Their design started with a generic rectangular shape, in contact with the skin and under each fitting. Since the thickness of the skin at the panels were the fittings are located is 0.09 inches, then the doubler was chosen to have 0.1 inches, which is the rule according to the SRM. The design of the doubler was made at the same time as the rivet pattern since they are driven by each other. In order to have a correct distribution of the rivets there was the need to identify the Keep Out Zone (KOZ), which is an area around each gusset that defines the minimum distance from which the center of the rivets can be, in order to avoid clashes. The KOZ was drawn at D+1 (mm) from each gusset's face. After having this, the stringer rivets were represented on the doubler, since they are an important reference. Finally, three design rules were followed, as explained in section 2.5.3 :

Rivet pitch between 4D-6D,

- Radius clearance of R+1 (mm),
- Edge distance of 2D+1 (mm).

With this in mind, the rivet pattern was created and the final doubler shapes were obtained. The doublers were designed with lobes at the stringer areas, in order to allow margin of adjustment at installation, since sometimes the stringer's rivet positions have an uncertainty associated with them. The final result is available in figure 3.18.



Figure 3.18: Doubler isometric view.

#### 3.3.1.4 Feedthroughs

The starting point for the feedthroughs positioning was looking at the ARINC 791, since it has some guidelines regarding this subject, which can be seen in figure 3.19



Figure 3.19: Feedthrough locations acording to ARINC 791 [36].

The green trapezoids show the areas where the center of each feedthrough should be installed. On the side of Y+, the feedthrough is used for the RF/IF electronics and on the Y- side it is used for the control and power connectors.

The feedthrough is the combination of a doubler (which can be seen in figure 3.18, and was made by using the same philosophy as the other doublers), and the cable seal which can be seen in figure 3.20.



Figure 3.20: Feedthrough design.

## 3.3.2 Internal Structural Installation

In order to help transfer the loads from the antenna's structure to the frames, an internal installation part was done, thus helping to reduce the stresses on the skin. This was achieved by connecting several larger sheet metal parts (intercostals) to the gussets and then to the frames. In figure 3.21 the intercostals are shown, as well as their connection to the frames, which will be explained next.



Figure 3.21: Isometric view of the internal installation.

First of all, the connection to the gussets was made by using eight fasteners (four on each intercostal) as seen in figure 3.21. The intercostals were then connected to the frames by using two T-brackets per intercostal. If the frame had a constant thickness then the design of the internal installation would stop here, however, this is not the case as it is presented in figure 3.10. Since they have pockets there was the need to use several shims (which are small machined parts), that make the connection between the frames and the T-brackets, in order to compensate the different frame thicknesses. The scheme from figure 3.22 was drawn in order to allow an easier understanding of why the shims are needed. The scheme was made by picturing a view in the Y positive direction (as depicted by the reference system from figure 3.21) and then rotating it 90° counter clockwise.



Figure 3.22: Shim schematic.

As it can be seen in figure 3.22, if the shim did not exist then the fastener on that area would not have a continuous material contact. By using the shims, this problem is solved and the connection between these two components (T-bracket and frame) is successfully made.

Additionally, by looking at figure 3.21 it is confirmed what was said before, that fitting 7 only attaches to one intercostal. In the past, these types of installations were always done with the same concept, which was, using two intercostals at every fitting's location however, it was seen that this philosophy was not necessary on fitting 7 because of the loading conditions. As seen from table 3.2 this fitting is only loaded in Z, which is not the most critical loading direction for an intercostal (that is Y). Although this concept was only used on fitting 7 it could also be tested on fitting's 2 and 6 since the loading conditions are similar, though a detailed analysis would be required. On the fittings with two loading directions, the best is to use two intercostals in order to transfer the load without damaging the part itself.

This change in the design came with the advantage of 2% weight saving of the installation, reason to why it seems interesting to, in the future, try and reduce more intercostals.

## 3.4 Full Installation and Further Work

By using all the remarks described in this chapter so far, the installation was completed and can be seen in figure 3.23.



Figure 3.23: Final external and internal structural installations.

After the external and internal installations were completed, their respective drawings were made, as well as the part drawings, like the doubler's and gusset's. A project does not end when the design is completed. In fact, afterwards, several analyses need to be done in order to certify the design, such as the static analysis, fatigue and Damage Tolerance Analysis (DTA), among others. These will check if the structural design is safe and if all the loads are according to the regulations imposed by EASA's certification specifications. The final part of the project will be to prepare all the documents needed in order to certify the installation, which is described in chapter 6.

## Chapter 4

# Quad Camera Structural Installation and Static Analysis

The quad camera technology can be used for a variety of applications such as ground maneuvering during taxi, in-flight entertainment and external security. Moreover, this system provides a 360° field of view by splitting the fields in four views : Forward, Aft, Left and Right [48]. It is usually installed at the lower fuselage of the aircraft, in order to fulfill the applications depicted above.

In this chapter, the structural installation of the quad camera will be designed and the static analysis of this system will be conducted, in order to check if the design is safe. Firstly, the camera position, environment definition and overall design will be presented, followed by the finite element method model definition, from the simplifications in geometry to the mesh convergence. Finally the results will be presented and discussed.

### 4.1 Camera Position

When positioning the camera it is important to take into consideration the horizontal and vertical fields of view of it, in order to guarantee the minimum amount of obstruction, which was found to be forward to the wings. It is normally not installed on the fuselage's center since the bending moments are considerably higher, which would make the modification certification a harder process and worsen the static analysis results. Furthermore, on the central fuselage there is the problem of obstruction of the side views of the camera, which would have a large angle covered by the aircraft's wings and engines. Additionally, if it was installed closer to the tail, then the front view of the camera would have the interference of the wings and engines as well, which is not desirable.

With this in consideration, the installation location was chosen to be between STA 718 – STA 739 and STGR 49L - STGR 49R since it fulfills all the costumer's performance requests. These stations are represented in Boeing's skin panel drawing in figure 4.1.

### 4.2 Environment Design and Structural Installation

The environment of this installation is much smaller than that of the Ka-band antenna since the modification only includes one frame bay (two frames) now. First of all, the skin was designed with the 122 inch radius known from the SRM. It was also seen that there was no skin pocket in this location, which made the design easier by providing more space for additional fastener installation. Afterwards, two stringers were modeled, with a certain degree of uncertainty since no drawing of its cross-section was available, which is why the most conservative approach needed to be considered. Small deviations may occur but there is margin of adjustment at installation given by the design. The value of the stringer's rivets pitch was measured from figure 4.1, by using mathematical proportions since it is known that between STA 718 and STA 739 the distance is 21 inches.



Figure 4.1: Quad camera installation area - red rectangle [49].

The installation design process started by analyzing the camera itself and its interface requirements. It has four holes that serve as attachments to the skin and a central connector, which can be seen in the camera data sheet in Appendix B.1. In order to perform the wire connection to the antenna, a fuselage penetration is required and thus a local reinforcement as well. One could think that a doubler would suffice in order to attach the camera to the skin but, since the camera attachment holes are very close to one another (closer than the general rule of minimum pitch of 4D), then this would result in a high stress concentration on that area (section 2.5.3), which would reduce drastically the number of cycles for crack propagation. For this reason an adapter plate was also created, with six fasteners that serve as attachments to the skin. Finally the rivet pattern was developed, having a circular shape around the cut-out and a more rectangular shape near the doubler's borders.

The connections between all of the components mentioned in the last paragraph, as well as the rivet

types, can be seen in figure 4.2.



Figure 4.2: Type of rivets used in the quad camera installation.

The four screws that attach to the camera are NAS24694-S50 (D = 4.762 mm, number 1), the fasteners that connect the adapter plate to the doubler are NAS517-3-5 (D = 4.826 mm, number 2), the stringer rivets are BACR15FV7KE (D = 5.556 mm, number 3) and the doubler rivets are NAS1097D6 (D = 4.776 mm, number 4). The six screws marked with the number 2 are then attached to nutplates which are used to keep them in place. Four extra sheet metal plates were used to install the nutplates on, thus preventing drilling the aircraft's skin with the non structural holes of the nutplates, that would be very close to each other. The internal part of the installation can be observed in figure 4.3.



Figure 4.3: Quad camera internal installation.

After having the design of all the 3D parts, the 2D part drawings could be made in order to do a conformity check, after production, to guarantee that all the parts fulfill the engineering criteria. The installation drawings were also prepared, which will give the workers instructions on how to install the camera, alongside some useful general notes and guidelines.

## 4.3 Quad Camera FEM

An important aspect of doing an installation is checking if it fulfills all stress requirements by performing different analyses, such as the static analysis and DTA. The starting point was to analyze the static behavior of the original design described in section 4.2, by using the software FEMAP [50]. Before starting to describe the problem it is important to understand what a static analysis is and how it is made.

The static analysis is done in order to calculate the margin of safety of a specific component that is being installed or already in place, like the aircraft's skin. In a simplified way, if the margin of safety is bigger than zero then the material is able to sustain the simulated load cases successfully, being then statically adequate [51]. If this analysis is not successful then the design should be changed.

The reference aircraft's coordinate system and sign convention used throughout this analysis is shown in figure 4.4.



Figure 4.4: Aircraft's coordinate system [52].

Unless stated otherwise, the units used for the different variables depicted in this chapter are presented in table 4.1.

Variable	Units		
Thickness	Inches (in)		
Area	Square Inches $(in^2)$		
Young's Modulus	Pound-Force per Square Inch (psi)		
Diameter	Inches (in)		
Pressure	Pound-Force per Square Inch (psi)		
Weight	Pounds (lb)		
Moment	Pound-Inch (lb.in)		
Moment of Inertia	Inches <sup>4</sup> ( $in^4$ )		
Stress	Pound-Force per Square Inch (psi)		
Force	Pound-Force ( <i>lbf</i> )		

Table 4.1: Typical units used for different variables.

#### 4.3.1 FEM Input Parameters

To obtain the margins of safety, a FEM model was built with the corresponding materials, geometries, properties, meshes, loads and boundary conditions. The starting point was the geometries and so, for that, the doubler, skin and stringers were modeled in a simplified way.

#### 4.3.1.1 Geometry

Firstly, the skin was represented without any curvature since it would not influence greatly the results because of the fact that the fuselage radius is very large and the installation is located at Y = 0 (where the effect of the curvature is minimum). The size of the skin panels Lx x Ly was defined as being more than 3 times the size of the doubler, so that the boundary constraints did not influence the stress field in the critical locations [52]. Furthermore, the doubler was modeled as a non curved plate, and the stringers were modeled as two straight lines below the skin. Finally the rivet pattern and larger cut-out were designed, by taking into consideration that an extra circle needed to be made around them, in order to assure a good and constant mesh in their vicinity, where the results should be as accurate as possible. The adapter plate and camera were not modeled (as well as their screws) since the inertial load cases were not simulated due the low camera weight (approximately 1 kg). In figure 4.5 the skin is represented by number 1, the doubler by number 2 and the stringers (not visible) by number 3, as designed in FEMAP.



Figure 4.5: FEM geometry components.

#### 4.3.1.2 Materials

After having the geometry, the materials were defined. The doubler is made of AL alloy 2024 T3, the skin of AL alloy 2524 T3 and the stringers of AL alloy 7150 T77511. In order to obtain the Young's modulus, density and Poisson ratio of these alloys, the Metallic Materials Properties Development and Standardization (MMPDS) was consulted, which has the properties for these different alloys, as accepted by government procuring and certification agencies [53].

#### 4.3.1.3 Properties

The skin and doubler were modeled with QUAD (square) and TRIA (triangle) plate elements, being only defined by a thickness  $t_{skin} = 0.1 in$  and  $t_{doubler} = 0.11 in$ . The stringer was modeled as a rod element, having thus a section area  $A_{stringer} = 0.1801 in^2$ , which was taken from the 3D environment made for the camera. Finally the rivets were modeled with spring elements (DOF Spring) which simulate shear and tensile stiffness and rigid elements (RBE3), which are used to model the rivet's contact on the skin and doubler. The spring's axial and shear stiffnesses [52] are calculated by using :

#### Axial Stiffness

$$K_z = \frac{E_f \times A_f}{L_f} \,, \tag{4.1}$$

where  $E_f$  is the fastener's Young's modulus,  $A_f$  is the fastener's section area and  $L_f$  is the fastener's grip length.

#### Shear Stiffness

$$K_y = K_x = \frac{1}{C} \,, \tag{4.2}$$

where C is the shear flexibility given by the Huth formulation as :

$$C = \left(\frac{t_1 + t_2}{2 \times D}\right)^a \times \left(\frac{b_1}{t_1 \times E_1} + \frac{b_2}{t_2 \times E_2} + \frac{b_1}{2 \times t_1 \times E_f} + \frac{b_2}{2 \times t_2 \times E_f}\right),$$
(4.3)

where :

- t<sub>1</sub> and t<sub>2</sub> are the thicknesses of plates 1 and 2,
- $E_1$  and  $E_2$  are the Young's modulus of plates 1 and 2,
- *E<sub>f</sub>* is the Young's modulus of the fastener,
- *a* is the coefficient that depends on the fastener type (2/3 for bolted/screwed joints, 2/5 for riveted joints),

- b<sub>1</sub> and b<sub>2</sub> are coefficients that depend on the joint plates material : b<sub>1</sub> = b/n and b<sub>2</sub> = b/n<sup>2</sup> (n = 1 for single shear, n = 2 for double shear, b = 3 for bolted metallic, b = 2.2 for riveted metallic and b = 4.2 for carbon fiber reinforced polymer),
- · D is the fastener's diameter.

From equation 4.1, the value of  $E_f$  comes from checking both the fastener's data sheets and the MMPDS after the material of the fastener is known. Furthermore, in this specific installation, from equation 4.3 the coefficients a = 2/5, n = 1 and b = 2.2 since all the fasteners used here are metallic rivets (recall that the screws of the camera and adapter plate are not being modeled).

For the stiffness calculation of the rivets that join three different thicknesses (doubler, skin and stringer), special attention is required, since the simple application of equation 4.1 and 4.2 won't suffice, due to the fact that the term  $t_3$  and  $E_3$  also exist now. The approach used by Jet Aviation, in order to model these type of rivets, starts by assuming that the axial stiffness is the same between the three plates, and calculated by considering that  $L_f = t_1 + t_2 + t_3$ . The shear stiffness is then calculated by using the thicknesses and materials of the surrounding plates, meaning that, if the spring is between plates 1 and 2 then  $t_1$ ,  $t_2$ ,  $E_1$  and  $E_2$  should be used. The detailed schematic explanation can be found in figure 4.6.



Figure 4.6: Rivet axial and shear stiffnesses with three plates.

#### 4.3.1.4 Mesh

It is important to guarantee that an accurate mesh is going to be used in the model. For that, a mesh convergence analysis was done and will be presented in section 4.3.1.7 since it required the use of the loads and constraints yet to be presented.

The mesh of this model will include different elements such as spring, rigid, plate and rod, as mentioned before. The first step was to mesh the surfaces and stringers by using the plate and rod elements respectively, followed by the rivet meshing. In order to model these last components two rigid elements and three coincident springs (with  $k_x$ ,  $k_y$  and  $k_z$ ) connecting them should be used thus simulating the connection between two plates, as seen in figure 4.7.



Figure 4.7: Doubler and rivets mesh (hidden skin for clarity).

Number one represents the rigid elements on the doubler, number two represents the rigid elements on the skin, which was hidden to allow an easier understanding of figure 4.7 and number three represents the stringer. As it is seen, the skin is connected to the stringer via three coincident springs and since the stringer was modeled as a line, no rigid elements were made there.

#### 4.3.1.5 Loads

The load subject needs a detailed investigation of the aircraft in study. For this reason, only a brief presentation of how the loads are calculated will be done, since it's detailed description is out of the scope of this thesis.

Fuselage loads are a combination of cabin pressure loads and fuselage bending which are used to estimate the longitudinal and circumferential stresses on the fuselage's skin [52].

#### Circumferential Stress

This type of stress is caused by the cabin pressure acting on the fuselage perimeter at the installation location, and is given by the following expression [52] :

$$\sigma_{circ} = \frac{P \times R_{Max}}{t_{skin}} \,, \tag{4.4}$$

where P is the cabin pressure,  $t_{skin}$  is the skin's thickness at the installation pocket and  $R_{max}$  is the maximum fuselage outer radius.

#### Longitudinal Stress

The longitudinal stress is due to the internal pressurization acting on the fuselage cross-section area, at the installation location, and is given by [52] :

$$\sigma_{long} = \frac{P \times A_P}{A_{fus}} \,, \tag{4.5}$$

where  $A_p$  is the fuselage's projected area :  $A_p = \pi \times R_{max}^2$  and  $A_{fus}$  is the fuselage's total crosssection area :  $A_{fus} = \sum A_{skinpanel} + \sum A_{stringer}$ .

#### Fuselage Bending Loads

The bending loads being presented are unitary, which means they are determined for 1G down load condition. They are calculated by following the method presented in [54] which starts by estimating the fuselage weight, presented in equation 4.6.

$$W = MZFW - 0.2MTOW, (4.6)$$

where MTOW is the maximum take off weight and MZFW is the maximum zero fuel weight. Another assumption is that the fuselage weight is distributed uniformly between the forward and aft pressure bulkheads, as seen in figure 4.8. This distribution is used in order to calculate the fuselage bending moment, which also takes into account the contribution of the tail, aft of the wings.



Figure 4.8: Standardized Weight Distribution [54].

In order to calculate the forward and aft bending moments, equations 4.7a and 4.7b are used, which use the variables from figure 4.8.

$$M_{fwd} = \frac{W x_{fwd}^2}{2L} , \qquad (4.7a)$$

$$M_{aft} = \frac{Wx_{aft}^2}{2L} + W_{tail}x_{tail}, \qquad (4.7b)$$

where L is the distance between the forward and aft pressure bulkheads, x is the distance from the forward/aft pressure bulkheads to the frame station where the bending moment is being calculated,  $W_{tail}$  is the tail's total weight and  $x_{tail}$  is the distance from the center of gravity of the tail to the frame station where the bending moment is being calculated.

With this it was possible to calculate the bending moment variation with the fuselage stations, which can be seen in figure 4.9 where the quad camera is represented by the black dot.



Figure 4.9: B777-200LR Fuselage bending moment.

By having the bending moment, the bending stress at 1G down can be calculated by using equation 4.8 [52] :

$$\sigma_{bending} = \frac{M_{bending} \times (Z_{ins} - Z_0)}{I_{yy_{fuselage}}},$$
(4.8)

where  $M_{bending}$  is the bending moment at the installation area,  $Z_{ins}$  is the coordinate Z at the installation area,  $Z_0$  is the coordinate Z at the neutral axis and  $I_{yy_{fuselage}}$  is the moment of inertia of the fuselage in the y axis.

#### Aerodynamic Loads

In order to have a more conservative approach when calculating these loads, the camera's shape was simplified into a cylinder. The aerodynamic drag's coefficient ( $C_D$ ) of a cylinder depends on the Reynolds number (Re) so, in order to be more conservative, the value  $C_D = 1$  was used since it corresponds to the  $C_D$  of most high Reynolds number (Re>100) cases in a cylinder [55]. The aerodynamic drag of the camera can then be calculated as seen in equation 4.9 [56] :

$$D_{camera} = \frac{1}{2} \times \rho \times V^2 \times A_r \times C_D , \qquad (4.9)$$

where  $C_D$  is the aerodynamic drag's coefficient,  $\rho$  is the air density at a considered altitude, V is the aircraft's velocity at a specific flight stage and  $A_r$  is the camera's reference area.

The cruise conditions were considered, for the drag calculation, and are characterized by [57, 58] :

- $Ma_{cruise} = 0.84$ ,
- $h_{cruise} = 35000 \ ft = 10668 \ m$ ,

- $a_{cruise} = 296.5 \ m/s$
- $\rho_{cruise} = 0.3797 \ kg/m^3$

where  $Ma_{cruise}$  is the mach number at cruise (cruise velocity divided by  $a_{cruise}$ ),  $h_{cruise}$  is the cruise altitude,  $a_{cruise}$  is the speed of sound at cruise and  $\rho_{cruise}$  is the density at  $h_{cruise}$ .

By considering these presented values and the fact that  $A_r$  (reference area) is the frontal area of the camera, which by analyzing Appendix B.1 is  $A_r = 49.225 \times 102.310 = 5036.21 \ mm^2 = 5036.21 \times 10^{-6} \ m^2$ , it comes that the drag force acting on the camera is equal to :  $D_{camera} = \frac{1}{2} \times 0.3797 \times 0.84^2 \times 296.5^2 \times 5036.21 \times 10^{-6} \times 1 = 59 \ N = 13 \ lbf$ 

Since this force is very small, even when considering a conservative  $C_D$ , then the aerodynamic loads are considered to be negligible.

#### Load Factors

From CS 25.337 [37] it was seen that there are rules to determine the positive and negative limit maneuvering load factors. The positive limit should follow these rules :

$$n_{maneuver_{LIM+}} = 2.1 + (\frac{24000}{MTOW + 10000}),$$
 (4.10a)

$$2.5g \le n_{maneuver_{LIM+}} \le 3.8g$$
. (4.10b)

The value of the MTOW can be obtained from the weight and balance manual [59] and comes as 750000 lb. By replacing it in equation 4.10a it comes that  $n_{maneuver_{LIM+}} = 2.13g$ , but since there is the limit set from equation 4.10b then  $n_{maneuver_{LIM+}} = 2.5g$ . Additionally, the minimum limit maneuvering load factor must not be less than -1g for speeds up to  $V_{cruise}$  and must vary linearly to zero from  $V_{cruise}$  to  $V_{dive}$ .

Furthermore, the gust limit load factors also need to be calculated in order to check if they are greater than the maneuvering limit load factors. The design ultimate vertical gust load factors are provided in Original Equipment Manufacturers (OEM) manuals for all body stations. For the camera's position it was seen that  $n_{gust_{ULT+}} = 5.1g$  and  $n_{gust_{ULT-}} = -1.5g$ . These values need to be factored down in order to obtain the limit gust load factors, which is presented in equation 4.11 :

$$n_{gust_{LIM}} = \frac{n_{gust_{ULT}}}{1.5} , \qquad (4.11)$$

where it comes that  $n_{gust_{LIM+}} = 3.4g$  and  $n_{gust_{LIM-}} = -1g$ . The maximum and minimum limit load factors of the aircraft will be the maximum and minimum between  $n_{gust_{LIM}}$  and  $n_{maneuver_{LIM}}$  which in this case means that  $n_{max_{LIM}} = 3.4g$  and  $n_{min_{LIM}} = -1g$ .

From here onward, only positive values of load factors will be used, making the distinction of their direction as down or up due to the fact that positive load factors result in a down load, whereas negative load factors result in an up load. Finally, the ultimate maximum vertical load factors are:

$$n_{down_{ULT}} = 3.4g \times 1.5 = 5.1g$$
, (4.12a)

$$n_{up_{ULT}} = 1g \times 1.5 = 1.5g$$
 . (4.12b)

Moreover, the emergency landing ultimate load factors, which will also be used for one of the load cases, are defined in CS25.561 [37] as being 6g down and 3g up.

#### Load Cases

The installation will be analyzed under four load cases that result from the combination of the pressure and bending loads, as well as the ultimate load factors, from which it is then possible to calculate the total longitudinal and circumferential load case stresses,  $\sigma_L$  and  $\sigma_C$  respectively, that are applied to the aircraft.

The first load case (LC101) is the combination of the longitudinal and circumferential pressure loads (ultimate) multiplied by 1.33 as it can be seen in equations 4.13a and 4.13b [52].

$$\sigma_L = \sigma_{long} \times 1.33 \times 1.5 \,, \tag{4.13a}$$

$$\sigma_C = \sigma_{circ} \times 1.33 \times 1.5 \,, \tag{4.13b}$$

where  $\sigma_{circ}$  and  $\sigma_{long}$  were obtained by using equations 4.4 and 4.5, respectively.

The second load case (LC102A) is the combination of the longitudinal load due to the flight envelope up and the ultimate pressure. In the bottom part of the fuselage, the internal pressure and up flight loads create tension, which means that both loads are added in order to calculate the total longitudinal load, as seen in equation 4.14a [52].

$$\sigma_L = \sigma_{long} \times 1.5 + n_{up_{ULT}} \times \sigma_{bending}, \qquad (4.14a)$$

$$\sigma_C = \sigma_{circ} \times 1.5 \,, \tag{4.14b}$$

where  $\sigma_{long}$  is given by equation 4.5,  $n_{up_{ULT}}$  is given by equation 4.12b,  $\sigma_{bending}$  is given by equation 4.8 and  $\sigma_{circ}$  is given by equation 4.4.

The third load case (LC102B) is the combination of the longitudinal load due to the flight envelope down and the ultimate pressure. Since now the flight loads are in the down direction, then a compression will be created in the bottom part of the fuselage. By this reason the bending contribution is subtracted in equation 4.15a [52].

$$\sigma_L = \sigma_{long} \times 1.5 - n_{down_{ULT}} \times \sigma_{bending}, \qquad (4.15a)$$

$$\sigma_C = \sigma_{circ} \times 1.5 \,, \tag{4.15b}$$

where all the variables are the same as in equation 4.14a and 4.14b except that now the variable  $n_{down_{ULT}}$  is used, taken from equation 4.12a.

Finally the last load case is the LC103 and represents the longitudinal load due to the emergency landing (ultimate). Since the most critical scenario is the down load factor, then the representative equation comes as such [52]:
where  $n_{EMERG_{ULT;Down}}$  is the ultimate emergency landing load factor down and  $\sigma_{bending}$  is the bending stress already depicted before.

It is important to note that all these equations were used to calculate stresses and not forces. In order to apply these load cases to the model there is the need to obtain the latter.

To obtain the longitudinal and circumferential forces equations 4.17a and 4.17b are used (applicable to all load cases).

$$F_X = \sigma_L \times t_{skin} \,, \tag{4.17a}$$

$$F_Y = \sigma_C \times t_{skin} \,. \tag{4.17b}$$

This gave a force per length, that could then be applied to the skin. The calculated longitudinal stress will also affect the stringer so a similar conversion needs to be done, in order to obtain the force applied on the stringer in each load case, as presented in equation 4.18.

$$F_{x_{stringer}} = \sigma_L \times A_{stringer} \,. \tag{4.18}$$

With the results from equations 4.17a, 4.17b and 4.18, the FEM model can be updated with the loads. This representation is presented in figure 4.10.



Figure 4.10: Loads represented in the FEM model.

#### 4.3.1.6 Constraints

The applied constraints were used in order to try and better approximate this model to reality, and can be seen in figure 4.10, in the four corners of the skin and edges of the stringers. In all the skin corners the third degree of freedom was always constrained, meaning that the skin could not move in the Z axis on those four edges. In addition, the remaining skin constrains were set to ensure a symmetric behavior of the model around the X axis. Finally, on the stringer the only allowable movement was in X and Y which goes into accordance of how a stringer should behave.

#### 4.3.1.7 Mesh Convergence

After determining all the parameters depicted in this section it was possible to do the mesh convergence of the doubler and skin. The mesh size was changed, starting with bigger elements and progressively decreasing the size of them. This will also automatically change the element number around each hole (skin and doubler) which will be one of the variables used to determine the convergence of the model, more specifically the number of elements around the stringer holes. Starting off with the skin, several iterations were done, having obtained the plot in figure 4.11.



Figure 4.11: Skin mesh convergence.

By analyzing the plot it is concluded that the convergence was achieved successfully since the Von Mises (VM) stress values are stabilizing. In order to choose the best mesh element number then a closer look at the FEM running time and results variation needs to be done. The computational cost grows exponentially from x = 44 onward, while the results have a small variation. From x = 44 to x = 54 the Von Mises stress had a variation of 4% while the computational cost increased by 64%. Due to this reason the number of elements chosen was 44, which is equivalent to a mesh size of 0.05 inches. Since the skin is the most critical component of the model, then its mesh should set the threshold for the mesh size of the other components.

The mesh convergence for the doubler was also done, in order to check if there was a convergence or not before the skin's mesh size. The plot is presented in figure 4.12.



Figure 4.12: Doubler mesh convergence.

The element number was measured on a same size hole which means that 44 elements in figure 4.12 is linked to the same mesh size as 44 elements in figure 4.11. The chosen element number was, again, 44, due to the imposed skin's threshold and already satisfactory convergence at this point.

Furthermore, the stringer's mesh size does not influence the results, since the connection to the skin is made by single nodes and not surfaces.

#### 4.4 Static Stress Analysis

As stated in section 4.3.1.5, four load cases were analyzed which corresponded to different load combinations. The results will be presented in a table form, for all the load cases, after the margins of safety equations have been deducted. In general, the margin of safety (MS) for the skin, doubler, and other components that are in tension or compression is calculated by using equation 4.19 [52].

$$MS = \frac{\sigma_{Tu}}{\sigma_{VM_{max}}} - 1, \qquad (4.19)$$

where  $\sigma_{Tu}$  is the ultimate tensile stress and  $\sigma_{VM_{max}}$  is the maximum Von Mises stress on the surface. As stated before, the margin of safety needs to be bigger than zero in order for the material to be able to sustain the loads. The Von Mises stress is being used to determine the margin of safety because this parameter takes into account different stress components such as  $\sigma_X$ ,  $\sigma_Y$  and  $\tau_{XY}$  [60], thus predicting the stresses on the model in a more accurate way.

Furthermore, in order to obtain the fastener's margins of safety, equation 4.20 should be used, where the maximum shear force applied to a specific fastener type should be taken from FEMAP and replaced

in it [52].

$$MS = \frac{\sigma_{Su} \times A_f}{S_{max} \times 1.5} - 1, \qquad (4.20)$$

where  $\sigma_{Su}$  is the ultimate shear stress of the fastener's material,  $A_f$  is the fastener's cross section area and  $S_{max}$  is the maximum shear force applied to the fastener. The factor 1.5 is included as a safety factor.

Finally another type of analysis that is usually done is the bearing's margin of safety calculation. The bearing forces exist due to the presence of a rivet in its hole which can cause deformation if the ultimate bearing load is surpassed. In order to calculate this margin of safety, the formula from equation 4.21 applies [52].

$$MS = \frac{t_{plate} \times D \times F_{bu}}{S_{max} \times 1.5} - 1, \qquad (4.21)$$

where  $t_{plate}$  is the thickness of the plate in which the fastener is going through (the bearing is analyzed at each component so it is not a problem if the fastener goes through two or more thickness layers), D is the fastener's diameter and  $F_{bu}$  is the bearing's ultimate load.

By running the model it was possible to obtain the Von Mises stress distributions on the skin and doubler as well as the shear loads on the fasteners, which can be seen in figure 4.13.





(a) Von Mises stress (psi) distribution on the skin

(b) Von Mises stress (psi) distribution on the doubler



(c) Shear loads (lbf) on the fasteners of the doubler

Figure 4.13: FEMAP results.

The maximum VM stress, which is highlighted in figure 4.13 a), will be used in equation 4.19 in order to obtain the margin of safety of the skin. This value was expected to happen at the cut-out, and in reality it does however, in the model, the stresses around the rivets are unrealistic due to the rigid elements, which explains the obtained results. This is not a problem and only means the model is more conservative. The maximum shear load of both fastener types can be seen in figure 4.13 c) and will be used in equation 4.20 and 4.21. In order to calculate the margins of safety more parameters needed to be defined, from the MMPDS and fastener data sheets, such as :

- $\sigma_{Tu_{skin}} = 60000 \ psi$
- $\sigma_{Tu_{doubler}} = 61000 \ psi$
- $\sigma_{Su_{NAS1097D6}} = 33000 \ psi$
- $A_{NAS1097D6} = \pi \times r_{fastener}^2 = \pi \times \frac{0.188^2}{4} = 0.02775 \ in^2$
- $\sigma_{Su_{BACR15FV7KE}} = 39000 \ psi$
- $A_{BACR15FV7KE} = \pi \times r_{fastener}^2 = \pi \times \frac{0.219^2}{4} = 0.03766 \ in^2$
- $F_{bu_{skin}} = 121000 \ lbf$

• 
$$F_{bu_{doubler}} = 125000 \ lbf$$

Where all the variables have already been defined on their own, being now the subscripts referring to the applicable component, like the doubler, skin, and both rivet types. By using these values, the Von Mises stress and the fastener's shear stress it was possible to calculate the margins of safety for the doubler, skin and fasteners, in all the load cases, which are represented in table 4.2.

Load Case	Skin MS	Doubler MS	NAS 1097D6 MS	BACR15FV7KE MS
LC101	0.636	1.319	0.350	3.161
LC102A	1.217	2.396	0.758	3.591
LC102B	0.714	1.349	0.231	2.413
LC103	0.861	1.726	0.535	2.462

Table 4.2: Skin, doubler and rivets margins of safety.

The margins of safety around the larger cut-out, on both the skin and doubler were also checked, in order to allow the comparison between the different load cases to see which one lead to the most critical results. They may or may not be the same as the skin and doubler's MS from table 4.2, due to the already mentioned unrealistic stresses due to the rigid elements. These values are presented in table 4.3.

Load Case	Skin MS at the cut-out	Doubler MS at the cut-out
LC101	0.798	1.319
LC102A	1.595	2.396
LC102B	0.890	1.349
LC103	1.089	1.726

Table 4.3: Skin and doubler margins of safety at the cut-out.

The bearing's MS were calculated by taking into consideration the maximum force of each rivet type, which is not perfectly accurate but it is a more conservative approach. These results are presented in table 4.4.

	Skin Bearing MS		Doubler Be	earing MS
	NAS	BACR	NAS	BACR
LC101	3.434	6.506	4.038	7.530
LC102A	4.775	7.281	5.562	8.410
LC102B	3.043	5.156	3.595	5.996
LC103	4.040	5.245	4.728	6.096

Table 4.4: Skin and doubler bearing's MS for both rivet types.

By looking at table 4.2 and 4.3 the first thing that is clear is that LC101 was the most critical load case for the skin and doubler while LC02B was the most critical load case for the rivets. Nonetheless, all the margins of safety were positive and so all components passed the static analysis. From table 4.4 it was possible to conclude that the bearing's margins of safety for both the skin and doubler were quite high, reason to why the bearing is usually never critical in these types of installations.

To sum up, this installation, which from here on is going to be mentioned as configuration 1, passed on the static analysis.

### **Chapter 5**

### **Design Improvements**

In a company environment and due to time constraints the priority is not always finding the optimum solution to an installation, but rather choosing a well functioning and known design. This sparkled an improvement strategy with the objective of achieving a lighter, cheaper and equally secure design for the quad camera. The design concepts were varied and the static analysis results and installation weight checked and analyzed. The cost analysis was also done, as well as a general understanding of the negative effects all design options can have on the aircraft. Finally the decision to whether invest or not in a new design was made, by taking into account all the parameters discussed throughout the chapter.

#### 5.1 Configuration 2

The first noticeable aspect when the quad camera design and FEM are analyzed is the doubler's size. Its high thickness alongside its length make it have a high impact in terms of the weight of the installation. Therefore, the investigation started by trying to reduce the doubler's size, in order to have a weight reduction. Another aspect that motivated this change was the fact that the doubler was sitting on top of the stringer, which meant that the stringer rivets needed to be replaced in order to place the doubler. When a rivet is removed, there is a high probability of needing an oversize rivet at the installation, in order to use that same hole. A larger fastener may concentrate more loads and thus lead to a crack initiation and propagation earlier than expected. Additionally, since there are less rivets to be installed then the probability of installation mistakes is also reduced. To sum up, in this case study, which will be called configuration 2, the doubler was reduced and is now between the stringers, as depicted in figure 5.1.



Figure 5.1: CATIA V5 model of Configuration 2.

Firstly, the weight reduction aspect was achieved having reduced it by 19.1%, which is a very good result. However, this new design can not be based only on the weight, it needs to take other aspects into consideration such as the static stress analysis.

For this improvement the static analysis was done, in order to determine the margins of safety and compare it to the original design. Since the doubler is smaller then what is expected is that the skin will be more loaded, while the doubler will be less loaded, when compared to the initial configuration. For the FEM the same parameters were used since the components were the same, and the fact that the doubler is smaller did not demand another mesh convergence analysis to be conducted. The new model's geometry in FEMAP is depicted in figure 5.2.



Figure 5.2: Geometry of configuration 2 in FEMAP.

As seen, even though the stringer's rivets were not being used by the doubler they were still represented, in order to have a better comparison between models, even though the results for their margins of safety will probably be unrealistically high. The analysis was ran for the four different load cases and the results were noted in tables 5.1 and 5.2.

The percentage increase or decrease in regards to configuration 1 is presented next to the relevant results, that were used to compare the configurations. This means that all results were used for model validation (checking if MS > 0), but not all were used for the comparison, due to the fact that the skin and doubler's margins of safety must be taken from the same zone in order to allow the comparison between configurations.

Doubler MS NAS 1097D6 MS BACR15FV7KE MS Load Case Skin MS LC101 0.472 3.035 0.334 (-4.5%) 5.034 (+59.2%) LC102A 1.104 4.392 0.794 (+4.7%) 6.858 (+91%) LC102B 0.585 2.377 0.392 (+69.8%) 7.489 (+210.4%) LC103 57.256 (+2225.6%) 0.781 1.440 0.523 (-2.2%)

Table 5.1: Skin, doubler and rivets margins of safety for configuration 2.

Table 5.2: Skin and doubler margins of safety at the cut-out for configuration 2.

Load Case	Skin MS at the cut-out	Doubler MS at the cut-out
LC101	0.472 (-40.8%)	3.035 (+130.1%)
LC102A	1.104 (-30.8%)	4.676 (+95.1%)
LC102B	0.585 (-34.2%)	2.377 (+76.2%)
LC103	0.938 (-13.9%)	1.440 (-16.6%)

As expected the skin was now more loaded (in all load cases) and the doubler less loaded (in all load cases except LC103). The doubler's rivets were approximately equally or less loaded than configuration 1, and the stringer rivets were less loaded now, which makes sense since they were not being used by the doubler, nonetheless these results should not be interpreted directly since they are not realistic. However, the general conclusion is that for the stringer rivets configuration 2 is better. Since the bearing is not critical, then its comparison to the original case is not important, hence why they are not shown in any table. However, the bearing margins of safety were checked and they were all positive and high like in configuration 1.

Although this new installation proposal leads to weight saving, it also increases the skin loads which is undesirable since that component is critical. The doubler is less charged overall, and so are the rivets, which is a positive aspect but it is not enough to single handily choose this new design over configuration 1. In order to validate this solution as an acceptable design, a detailed DTA analysis needs to be executed in order to determine the new threshold and intervals of inspection of such installation. If the results are not much different than the already existing inspections given by the OEM, then the solution should be chosen.

Regarding the cost, the only difference in it will be in the installation cost since, as less holes need to be drilled on the skin, then less time will be needed to do set installation, thus reducing the cost for

the company. This installation needs two technicians that have, each, a cost of 97€ per hour for the company. If the installation takes less two hours for example, then about 388€ are saved. If this concept is applied to other similar installations on other aircraft, this cost reduction will be more noticeable. This analysis serves as an example of design to weight and design to cost approach, that is crucial in the aerospace industry.

#### 5.2 Configuration 3

A different approach was tested in order to try and reduce the stresses on the skin of configuration 2. In this third case, called configuration 3, L-brackets were placed on the inside of the aircraft connected to the doubler and stringer, as a way of load transfer, thus trying to lower the stresses on the skin. Alongside this four stringer attachments were added, with the objective of stabilizing the installation as well as transferring some loads to the stringers. Additionally, there are shims that make the connection between the L-brackets and the skin which are not going to be represented on the finite element model since they do not have a structural function. The design can be seen in figure 5.3.



(a) Configuration 3 exterior aircraft view



(b) Configuration 3 interior aircraft view



Unlike configuration 2, due to the addition of the extra sheet metal parts, the weight saving objective was not achieved, having increased the installation weight by 3.49%. The production cost of this configuration is also higher since more parts will need to be produced, even machined ones. The installation cost is not as easy to quantify since, although less rivets are being replaced in the stringer, others are being added on the stringer attachment clips (four per clip). That is why it was assumed that the overall cost was the same as in configuration 1. The static analysis results were checked in order to conclude whether this installation helped to reduce the skin's stresses or not.

The same strategy depicted in chapter 4 was used, having defined all the materials, properties, meshes, loads and constraints. The L-brackets and stringer attachments were considered to be made of the same material as the doubler, having each a thickness of 1.6 mm. The stringer was modeled, not by using a line, but by using three surfaces which had the thicknesses of the stringer from the 3D model. The parts were then put in place in order to obtain the design presented in figure 5.4.





(b) Configuration 3 geometry of the aircraft interior

Figure 5.4: Configuration 3 representation in FEMAP.

Since now there are more surfaces, then it is necessary to do the mesh convergence on the new parts (L-brackets, stringer attachments and stringers), in order to have accurate model results. It was observed that the VM convergence was already satisfactory at the same mesh size as the skin, for all three new parts, reason to why it was chosen.

The results were taken by using the same method as before. The only difference is that the margins of safety of the L-brackets, stringer attachments and stringers were also seen, in order to guarantee that the parts were not being over stressed. Even though they are not being presented, their margins of safety were all bigger than zero. The skin, doubler and rivets results can be seen in tables 5.3 and 5.4.

Load Case	Skin MS	Doubler MS	NAS 1097D6 MS	BACR15FV7KE MS
LC101	0.490	3.278	0.218 (-37.7%)	1.191 (-62.3%)
LC102A	1.095	3.203	0.728 (-4.0%)	1.028 (-71.4%)
LC102B	0.622	2.245	0.235 (+1.7%)	4.198 (+74%)
LC103	0.640	1.067	0.399 (-25.2%)	0.664 (-73.0%)

Table 5.3: Skin, doubler and rivets margins of safety for configuration 3.

Table 5.4: Skin and doubler margins of safety at the cut-out for configuration 3.

Load Case	Skin MS at the cut-out	Doubler MS at the cut-out
LC101	0.490 (-38.6%)	3.278 (+148.5%)
LC102A	1.095 (-31.3%)	3.479 (+45.2%)
LC102B	0.622(-30.1%)	2.245 (+66.4%)
LC103	0.736 (-32.5%)	1.071 (-38%)

By analyzing the results it is possible to conclude that, on two of four load cases the skin's cut out MS got increased (when compared to configuration 2), which by itself does not mean the design is better. In fact, the skin's MS at the cut-out has still decreased when compared to configuration 1 (which can

be seen by taking a look at the percentages from table 5.4), which means that the new design does not produce satisfactory results when it comes to the skin as well.

#### 5.3 Configuration 4

There was another design variation approach that could be followed which resided in adding another design variable: the doubler's thickness. Instead of reducing the doubler, its thickness could just be changed in order to analyze how it influences the skin and rivets stress since it might be a better strategy to do so.

Normally the philosophy in Jet Aviation is always to choose the thickness of the doubler based on the SRM. This means that if the skin is 0.1 inches thick then the doubler is recommended to have at least 0.11 inches of thickness. This might not be the lightest option however, which is what motivated this investigation.

In order to choose the new doubler's thickness, there are rules that should be followed. According to [51], the relation between the skin's and the doubler's thickness should follow equation 5.1.

$$1 \le StiffnessRatio = \frac{(E \times t)_{doubler}}{(E \times t)_{skin}} \le 1.5.$$
(5.1)

Where  $(E \times t)_{doubler}$  represents the Young's modulus and thickness of the doubler, and  $(E \times t)_{skin}$  represents the Young's modulus and thickness of the skin. The structural installation is adequate if the stiffness ratio is between 1 and 1.5, being considered too stiff when the value is greater than 1.5 and not stiff enough when it is less than 1.0.

The values of the Young's modulus were taken from the MMPDS, being  $E_{doubler} = 10500 \ ksi$  and  $E_{skin} = 10300 \ ksi$ . Additionally, on the installation area the thickness of the skin is  $t_{skin} = 0.1 \ in$ . By replacing these variables in equation 5.1 it came that the thickness of the doubler should be between 0.098 and 0.147 inches. Since one of the objectives of the improvement is achieving a weight reduction, then the only thickness that will be tested is the gage (standard sheet metal thickness) near the minimum, which is 0.1 inches. This new improvement strategy will be referred to as configuration 4.

The first step was to change the thickness of the doubler in the original FEM model. The spring element properties were also updated, since they depend on the thickness of the doubler, as seen in chapter 4. The results are presented in tables 5.5 and 5.6.

Table 5.5: Skin, doubler and rivets margins of safety for configuration 4.

Load Case	Skin MS	Doubler MS	NAS 1097D6 MS	BACR15FV7KE MS
LC101	0.642	1.212	0.417 (+19.2 %)	3.388 (+7.2 %)
LC102A	1.227	2.241	0.844 (+11.3 %)	3.827 (+6.6 %)
LC102B	0.731	1.240	0.293 (+26.8 %)	2.527 (+4.7 %)
LC103	0.841	1.599	0.612 (+14.5 %)	2.641 (+7.3 %)

Load Case	Skin MS at the cut-out	Doubler MS at the cut-out
LC101	0.746 (-6.5 %)	1.212 (-8.1 %)
LC102A	1.522 (-4.5 %)	2.241 (-6.5 %)
LC102B	0.831 (-6.6 %)	1.240 (-8.1 %)
LC103	1.029 (-5.6 %)	1.598 (-7.4 %)

Table 5.6: Skin and doubler margins of safety at the cut-out for configuration 4.

By analyzing the results it is possible to conclude that the fasteners margins of safety have increased, since the shear force acting on them is lower, due to the reduced area surrounding them (because of the reduced doubler's thickness). On the skin and doubler the stress has increased, which means that the doubler is taking more loads than on configuration 1 but because of the reduced thickness it is not able to protect the skin as efficiently as in the first configuration. The weight saving objective was achieved, since now the doubler weights 10% less than on the first configuration. The cost of the installation and production will remain the same as on configuration 1, since the design concept has not changed.

#### 5.4 Configurations Comparison

In order to compare the results, the lowest values of the margins of safety for each comparison parameter were taken for all four configurations, since it represents the critical case. The results were presented by using a spider chart (figure 5.5), which represents the results from configuration 2, 3 and 4 in regards to 1. An additional line was made in red that represents MS = 0 which is the limit case.



Figure 5.5: Comparison between configurations 1, 2, 3 and 4

The first thing that is clear when analyzing figure 5.5 is that configuration 3 is never the best one in terms of static analysis. This aspect combined with the increase in weight make it a non-viable option for this type of installation. Additionally, configuration 4 has a very similar profile of margins of safety to configuration 1, and a weight reduction of 10%, while configuration 2 has a noticeable reduced margin of safety on the skin (although it is still far from the red boundary), but other advantages which should not be undermined such as the 19.1% weight and cost reduction.

Based on all the data presented and by taking into consideration the weight saving and cost reduction, as well as the static analysis results then it is concluded that the design of configuration 2 would be very interesting to pursue, which means doing the fatigue and DTA analysis and then comparing it with configuration 1. If those extra analyses led to similar results when compared to configuration 1, then it would be beneficial for the company to choose the improved design. In case the results do not prove that configuration 2 is better, then the fatigue and DTA of configuration 4 should be done, since it also shows promising static stress results. Nonetheless, in this phase the only conclusion that can be taken is that a deeper investigation should be done to these two configurations.

### **Chapter 6**

# Certification and Compliance Documents

A modification project does not end when the design and its stress analyses are finished. In fact, there are several documents that need to be approved in order to certify the installation via an STC.

This documentation is often divided into two categories which are the certification documents and the compliance documents. The purpose of the latter is to prove compliance to the different certification chapters found on the applicable regulations of the certifying authority. The certification documents, on the other hand, summarize all the certification aspects of the modification and guarantee that all certification chapters impacted by the modification are addressed.

All departments are concerned by the preparation of this documentation being the certification department responsible for giving the final approval. Below, a brief summary of some of these documents is presented.

#### 6.1 Project Description (PRD) and Master Data List (MDL)

The project description must be one of the first documents to be created. Its objective is to give an overview of the project and share some details about the modification location and function. It is important that all modified air transport association (ATA) chapters (which are numbering systems and referencing standards for commercial aircraft documentation) are listed [61]. In addition it must present a brief summary of the certification basis of the aircraft, as well as the certification basis that the design organization elects to comply with. Finally, a list of the way the different documents are organized within the modification is made. The PRD is important in order to initiate the discussions with the authorities, as well as to understand the modification more easily.

The MDL lists all compliance and certification documents that are part of the modification package which will be submitted in order to obtain the STC.

#### 6.2 Classification Assessment and Application Form (CAF)

The CAF is the first certification document issued and has a high importance since it determines the type of modification of the project, and thus the level of involvement of the certification authorities. It contains several queries about the modification that will eventually result in the conclusion of whether the current modification is minor or major.

If the classification is minor, then it means that the certification office of Jet Aviation can approve the modification due to the privileges given by EASA. These privileges exist because Jet Aviation has a design organization approval which is the recognition that it complies with the requirements of Part 21 J of the regulations.

On the contrary, if the classification is major (which is the case of both modifications presented in this thesis) then the approval will normally be given by an STC, which means that the certification authorities need to be involved. Lastly, this document must define the certification basis that will be used to certify the modification, which must be respected by all the compliance documents.

#### 6.3 Certification Compliance Sheet (CCS)

The CCS is a certification document that provides the list of compliance addressed by the modification. It states the same certification basis stated in the CAF and all compliance chapters concerned by the modification undertaken. To each chapter it specifies the means of compliance used, as seen in figure 6.1, that can range from statement, design review, testing, safety assessment, equipment qualification etc. In addition, each of the compliance documents created is stated on the respective chapter it concerns.

Type of Compliance	Means of Compliance	Associated Compliance Documents
Engineering evaluation	MC0: - Compliance statement - Reference to Type Design documents - Election of methods, factors - Definitions	Type Design documents Recorded statements
	MC1: Design review	Descriptions Drawings
	MC2: Calculation/ Analysis	Substantiation reports
	MC3: Safety assessment	Safety analysis
	MC4: Laboratory tests	Test programs
Tosts	MC5: Ground tests on related product	Test reports
10313	MC6: Flight tests	Test interpretations
	MC8: Simulation	
Inspection	MC7: Design inspection/ Audit	Inspection or Audit reports
Equipment qualification	MC9: Equipment qualification	Note: Equipment qualification is a process which may include all previous means of compliance

Figure 6.1: Different means of compliance and corresponding documents.

#### 6.4 Drawing List Mechanical (DLM)

The DLM includes all the drawings related to the mechanical part of the installation, as well as bills of materials, deviations and the applicable revisions of each of these documents. The objective of the DLM is to list all the compliance chapters to which compliance must be shown by the drawings on the list. The certification office will then revise the content of all the drawings against the certification requirements and ensure its compliance by design review. In conclusion, this is a compliance document which approves the design and gives the authorization to use the listed drawing revisions on a certain aircraft type.

#### 6.5 Drawing List Electrical (DLE) and Electrical Item List (EIL)

The DLE has the same functions as the DLM but it contains electrical drawings instead of mechanical drawings.

Besides this list, the EIL also needs to be prepared, and it includes the list of all electric equipment needed for the installation and the corresponding drawings where they are used.

#### 6.6 Subcontractor Document Process Slip (DPS)

In the modifications described in this thesis there are design data (drawings) that were prepared by other companies, who supplied some of the components for the installations. Although these drawings contain all necessary design instructions, the DPS is needed to list which compliance chapters will be addressed by these subcontracted drawings, in order to approve them.

#### 6.7 Engineering Order (ENO)

The engineering order contains the orders of the engineering department, which include instructions for the production of the parts, removal and installation. It also has the confirmation of embodiment of the task and the list of documents that will impact each respective aircraft manual.

#### 6.8 Weight and Balance Statement (WBS)

When doing a modification in an aircraft its weight will suffer alterations, increasing or decreasing depending on the modification that is being made. It is important to register the weight changes since it affects the aircraft's center of gravity position and, therefore, needs to be updated in order to allow the correct control of the aircraft, by the pilots. Additionally, the bending moments that the new weight produces are also calculated in order to update the bending moments acting on the aircraft, which will affect stability. The longitudinal location of the aircraft's components center of gravity is referred to as balance arm, which is the distance measured in inches to the reference of 92.5 inches, as seen in figure 6.2. This reference varies from model to model so it should be checked every time. The balance arms are equivalent to body stations which means that, if a component is on the 1455 STA then the balance arm is 1455 - 92.5 = 1362.5 inches. If this value is multiplied by the weight of the component then the moment produced by it is determined.



Figure 6.2: Balance arm reference system for the B777-200LR [59].

### 6.9 Structural Substantiation Report (SSR) and Damage Tolerance Analysis (DTA)

The SSR is the report where the static analysis of the installation is presented and the FEM model of it introduced. The objective is to determine the margins of safety, in order to prove that the system passes in the static analysis. The analysis included in the SSR was done in chapter 4.

The DTA analyzes the crack initiation and propagation, with the final objective of obtaining the new intervals of inspection required to apply on the aircraft, in order to identify cracks before their behavior becomes unstable.

#### 6.10 Instructions for Continued Airworthiness (ICA)

The objective of this document is to provide instructions to be added to the maintenance tasks of the aircraft, in order to ensure continued airworthiness after the modification. In the case of the Ka-band modification it includes a description of the system and a guide on how to disassemble and get access to additional components that require maintenance. Furthermore, a section is added to list the proposed scheduled maintenance required after the modification. In the case of the Ka-band and based on the results of the DTA analysis, this comes as more strict intervals of inspection than those already existing, and possibly new means of inspection due to the additional doublers introduced by the design.

#### 6.11 Analysis Report (ANA)

Analyses are often used to show compliance, like the beacon's light analysis made in chapter 3. This type of document can be used to a very diverse range of topics to which it is decided that an analysis is the best way to show compliance.

#### 6.12 Flight Test Plan (FTP)

For some modifications a flight test may be required, by the authorities, in order to show compliance to the regulations and prove the safety of the modification. In the case of the Ka-band antenna, a flight test is required to compare the structure vibrations before and after the modification. It is important that all procedures and expectations of the flight test are clearly stated on the flight test plan, in order to ensure the accuracy and validity of the results. In addition, this test must always be witnessed by a certified staff member for the discipline in question.

#### 6.13 Aircraft Flight Manual Supplement (AFM)

This is neither a compliance nor a certification document, nonetheless it is an important supplement to the aircraft's flight manual with the objective of providing information to the pilots about the changes after the modification. In the case of the Ka-band antenna, this document would provide information to the pilot on how to operate the new control panel added to the cockpit, how to consider the changes in performance (both weight and aerodynamic) and how to proceed in case of an anomaly or interference with the aircraft primary electronic and communication systems.

Once all the documents are released then the STC application can go forward to the competent authority, in this case EASA, which will then approve the modification if all the requirements are fulfilled.

### **Chapter 7**

### **Conclusions and Future Work**

This final chapter presents the conclusions of this thesis and does recommendations for future work that can be pursued inside this subject.

#### 7.1 Conclusions

The primary objective of this thesis was to present aircraft modifications, as done in an industry environment, while showing two different installations : a Ka-band antenna and a quad camera. Although they are different systems their designs go through some similar processes such as choosing the installation location and defining the aircraft's environment on that area, which is one of the key aspects in order to have a successful design.

Furthermore, the industry standards such as the ARINC 791 are used in order to ease the design of the structural modification, through the use of already existing instructions. The design guidelines, such as the inter-rivet pitch, have a scientific background behind them which means that, by following the proven design rules, the analysis and calculation efforts are considerably reduced, which is a positive aspect when it comes to a project budget. The design of the Ka-band antenna was successfully done, being in conformity with the stress department's considerations. The stress analyses will still need to be approved, however the results are expected to be respecting all the certification specifications.

Regarding the quad camera, the design was also approved and, as seen in chapter 4, the static stress analysis gave good results. The second biggest objective of this thesis was trying to do an improvement to the already existing camera design, in order to achieve weight and cost reductions, which would benefit the company and the customer, without compromising the integrity of the structure. Three configurations were tested and from those three options it was seen that configuration 2 and 4 produced the most promising results, in terms of static analysis results and weight. In regards to the original design, configuration 2 achieved a 19.1% weight and cost reductions, having acceptable margins of safety at all the components except on the skin, where there was a more noticeable decrease, although it was still within the acceptable limits. Additionally, configuration 4 achieved a 10% weight reduction having similar stress results to what was obtained in configuration 1. The next step would be to do the

the fatigue and DTA in order to determine the inspection intervals of the installations. In case these intervals are acceptable in configuration 2 or 4, or both, then a decision will need to be made in order to choose the best solution.

At last, the documentation needed for the certification of the modifications was presented, as a way of showing that a project does not end when the design and stress analyses are done. It is much more than that, since several documents need to be prepared in order for the modification to be certified.

#### 7.2 Future Work

In terms of future work several opportunities have been identified, which will continue this thesis work and even go further than that.

The first topic is related to the intercostal design in the Ka-band antenna installation. As it was seen, in fitting 7 it was decided to use only one intercostal because of the loading condition in the Z axis. At that time it was only discussed with the stress team to change the intercostals from fitting 7, but if a more detailed investigation is done it might result in the conclusion that probably fittings 6 and 2 can also have a single intercostal, due to their loading conditions. The current design might be adding unnecessary weight where it is not particularly needed.

The second topic is related to the quad camera improvement done in chapter 5. An interesting continuation to it would be in the field of the fatigue and damage and tolerance analysis, since these analyses need to be done in order to conclude if configuration 2 or 4 are better than the original or not.

The last suggestion for future work came from having done the structural designs, most specifically the rivet patterns. This part of the design has a great influence on the stress distribution of the doubler and skin and should also be improved. A good tool to develop in the future is a tool that links both static and DTA analyses and designs the rivet pattern automatically in order to have the best results of stress. The rivet positioning is a time consuming task so if this tool were to be developed it would be beneficial for the company.

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## Appendix A

# **Additional Content**

A.1 B777-200LR Aircraft Layout



### Appendix **B**

# **Technical Datasheets**

B.1 Quad Camera Data Sheet

