Design of a Wind Tunnel Force Balance

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Abstract

Wind tunnels are used to simulate the behaviour of models in the presence of an airflow thus allowing to obtain the components that better define this interaction, forces and moments. In order to take full advantage of the Aerospace Engineering Laboratory's wind tunnel at Instituto Superior Tcnico, it has proved necessary to design a balance to measure forces and moments. Firstly, the force balance dimensioning was based in the possibility of testing both aircraft and half-wing models that fit the wind tunnel test section, using a simulation software (*XFLR5*) to obtain the maximum load range the force balance has to be able to support in each of the situations. The Analytic Hierarchy Process and a set of comparison criteria allowed the selection of the most adequate force balance architecture from the most widely used, the external platform balance. Once the "skeleton" of the force balance was defined, it was necessary to carefully define each of its mechanical components and guarantee that its integrity was fulfilled using the software *SolidWorks*. This is followed by the selection of all the electronic components like strain gauges and data acquisition system that will assess the deformation of the balance for a certain loading condition. Several considerations on the mechanical assembly were made and a cost analysis was presented. Finally, it is suggested a calibration procedure to make the force balance fully functional.

Keywords: Six components aerodynamic balance, Experimental testing, Mechanical design, Sensors and instrumentation, Calibration procedure

1. Introduction

The market demand in the aeronautical industry has driven its continuous development during the last decades. This fact is due not only to the increasing needs of the society but is also made possible because of the development of science and technology that we have assisted in the past decades.

In the aerodynamics field, in particular, the existing theory along with better experimental conditions allowed a better understanding of the aeronautical specifications and made more efficient and high-performing aircrafts possible. Among the many tools available to fulfil those purposes, the one we will be analysing through this document is the wind tunnel.

Wind tunnel testing is one of the most important experimental tests to assess the aerodynamic performance of different parts not only in aircraft but also in rockets, cars or even in buildings. By subjecting the model in test to an air flow, we can determine forces and moments acting along the structure. It is also important to note that, usually, because of the available dimensions of the wind tunnel test sections, it is used a model that is smaller than the original one.

Since this is a topic of interest, any possible development or advantage will be very welcomed. For this reason, it will be carried out a full analysis of wind tunnel testing mainly regarding the devices used to measure forces and moments: the force balances. In general terms, this device can present several configurations depending on its purpose.

We will be addressing this last topic and constructing a force balance to be used in the Aerospace Engineering Laboratory's wind tunnel and so, detailing the theoretical background as well as the chosen approach to do so.

This force balance has to measure six components of aerodynamic forces (drag, lift and side) and moments (pitching, rolling and yawing) and it is supposed to be fully adapted to our measuring reality. It is, for this reason, necessary to conduct a full analysis regarding not only the solutions already available along with our measuring objectives but also the new possible developments that can bring some value and innovation to this project. First of all, it is necessary to identify the measuring requirements of the force balance in order to select the most adequate concept. After that, its mechanical and electrical design has to be performed that will result in a set of components that have to be design and bought. Finally, this set of components will result in a manufacturing and assembly plan that has to be followed. After that, a possible calibration process for the force balance will also be outlined.

2. Background

2.1. Wind Tunnels

In general terms, we can divide all types of wind tunnels in two major groups: open circuit wind tunnels and closed circuit wind tunnels.

Regarding open circuit wind tunnels, the air flow follows a straight path and flows from the entrance to the contracted zone where the test section is located and then passes through a diffuser, a fan section and an exhaust. Regarding the boundaries, that is, the "limit" of the wind tunnel, they may be solid or not.

As the name suggests, closed circuit wind tunnels (also known as closed return, Prandtl or Göttingen wind tunnels) are characterized by the recirculation of the air flow. In fact, the exchange of air with the exterior is very small. This kind of wind tunnel usually has a single return, meaning that the air flows through one specific path. Like the ones stated before, the test section of these wind tunnels can be open or closed.

2.2. Force Balances

In a simple way, we can say that a force balance is a device used to directly measure forces and moments acting on the model that is being tested in the wind tunnel. Desirably, a good force balance should be able to provide separated values of force and moment components. Additionally, we can say that any wind tunnel rises from the necessity of having maximum load capability in all measuring components along with the accuracy for measuring minimum loads.

A model to be tested can be mounted by struts to the balance which lays outside the wind tunnel test section, in this case we have an external wind tunnel force balance. On the other hand, we can have the balance inside the model itself connecting the model to the support structure, in this case we have an internal force balance [2].

Besides the structure of the force balance itself, there are several systems that are necessary to obtain the desired results. Coupled to the frame of the force balance, there are extensometers that will measure the strain of the loaded structure. The output voltage of these sensors is then post-processed in a data acquisition system which is associated with a specific software that will return the correspondent strain values. After a previous and careful calibration process that concludes the construction of the force balance, it is possible to come up with the loading state of the model, in terms of force and moment components, based on the obtained values of strain. The schematic represented in figure 1 explains the overall process. A detailed explanation on the referred components will be carried out in the next sections.

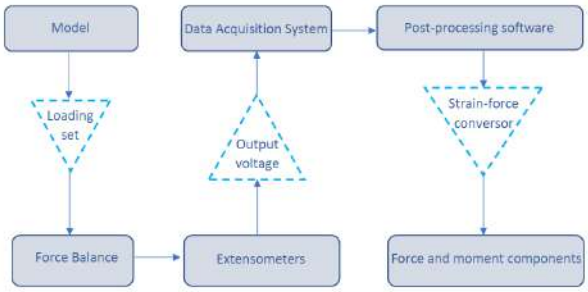

Figure 1: Schematic representation of data acquisition procedure using a force balance

2.3. Sensors and Data Acquisition Systems

Besides the main structure of the force balance, several devices have to be connected in order to measure and obtain the results and so making it fully operational.

One important factor regarding wind tunnel testing is the way forces and moments are measured. There are several methods available in the market that we can apply to a force balance, however there are advantages and disadvantages that lead to a choice that will be dependent on the force balance to be used. In general, they can be divided in two major groups: hydraulic measuring device and electrical measuring device. The former is a device that measures force values through the pressure exerted on pistons that have a certain known value of area. This pressure is a function of the load and is measured using pressure gauges. As for the latter, there are many options to measure forces and moments electrically, being the most widely used the strain gauges, that can present a wide range of different properties, and piezoelectric force transducers. Usually, in force balances applications, the electric load measurement techniques are preferred. These sensors require the use of data acquisition systems (DAQ) as the output electrical signals of the strain gauges have to be decoded to the actual values of strain. This devices, associated with specific software, play an important role as an interface between a computer, where the results are to be analysed, and the loads that act on the system being tested.

Another important quantity that has to be monitored is the air stream velocity. There are many techniques to measure it, although some are more adequate and present more advantages than the others, regarding this specific application.

Finally, in order to control the position of the models that are going to be tested, it is necessary to use devices that provide the attitude, since the forces and moments acting on the object are greatly dependent on its orientation.

3. Requirements and Conceptual Analysis

3.1. Wind Tunnel Specifications

In order to dimension the force balance, it is important to know the internal dimensions of the wind tunnel, in particular the ones that refer to the test section. A schematic representation of the wall that contains the nozzle is shown in figure 2, along with its characteristic dimensions (in centimetres).

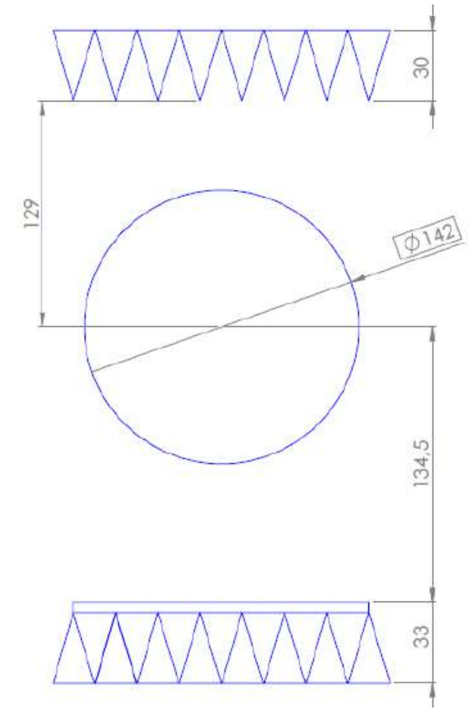

Figure 2: Schematic representation of the wind tunnel - internal dimensions of the nozzle section

Given the nozzle dimension and taken into account the growth of the mixing layer of the jet, it is expected a test section with no more than 100 *cm* of diameter.

3.2. Testing Scenarios

In order to accurately measure all of these components, it is mandatory to define the reference axis on the wind tunnel. Figure 3 represents the three components of the wind axis in a simplified scheme of the wind tunnel test section and the subscript w stands for *wind*. X_w is the wind longitudinal axis which is parallel to the wind tunnel flow but is defined in the opposite direction. Y_w is the wind lateral axis which is perpendicular to the wind x-z plane and positive defined by a right-handed system, being the Z_w the vertical wind axis.

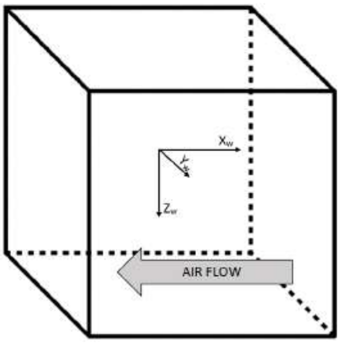

Figure 3: Schematic representation of the wind tunnel test section and of the adopted reference axis

Based on the predictions concerning the hypothetical models to be tested, two main options arise. We can study the aerodynamic forces and moments distributions on an isolated wing; in this case, it is common to test half wing models and extrapolate the results to the full wing model. Another option is to use a complete model of an aircraft with wing, fuselage and stabilizers. These two scenarios are very different from one another in terms of loading distribution so a carefully detailed analysis will be performed for each of the options in the next sections.

3.2.1 Half Wing Model

Considering the case of a wing, it will be assumed to have a low aspect ratio ($AR = 4$) and, giving the fact that we will be testing half wing models, a half-wingspan of $1\,m$, guaranteeing that half of the wingspan is shorter than the maximum diameter of the test section. A NACA 4412 airfoil was selected in order to get the maximum lift coefficient in the wing due to its high camber. Considering the airflow velocity, let us consider a maximum value of $50\,m/s$, in order to get a more critical solution.

Two design approaches will be investigated: the first corresponds to the wing without flaps and the second corresponds to a wing with 10° trailing edge flaps that start at 65% of the wing.

Now that the airfoil is selected and the designs are defined, it is possible to use a simulation software (*XFLR5, v6.40* [1]) to estimate aerodynamic loads that will be acting on the model. The range of simulations to be performed gives us the aerodynamic coefficients of the wing model, namely, lift and drag forces and pitching moment coefficients, thus allowing us to obtain an approximate range of aerodynamic forces and moments. We have to note, however, that the goal of this simulation is not to obtain the exact values of these quantities but instead be aware of the order of magnitude that the balance has to be able to support and measure.

The maximum expected forces and moments for the three half-wing designs are represented in table 1.

Airfoil	AR	F_X $[N]$	F_Y $[N]$	M_X $[Nm]$	M_Y $[Nm]$	M_Z $[Nm]$
NACA 4412	4	101	944	472	50	63
NACA 4412 - TE flap (10°)	4	169	1171	585	84	55

Table 1: Half wing aerodynamic loads

It is possible to verify that the maximum values of forces and moments occur for the wing with the 10° trailing edge flap. If we consider this model to be tested with a sideslip angle of 20°, it is possible to obtain the results presented in table 2.

β [°]	F_X $[N]$	F_Y $[N]$	F_Z $[N]$	M_X $[Nm]$	M_Y $[Nm]$	M_Z $[Nm]$
0	169	1171	0	585	84	55
20	213	1025	45	524	115	60

Table 2: Expected maximum loads and moments

3.2.2 Full Aircraft Model

Another simulation can be performed to evaluate the behaviour of an aircraft model composed of main wings, tail and fuselage. The fuselage measures 1.1 m and the leading edge of the wing is placed 0.3 m after the fuselage nose. The wing has an aspect ratio of 4 which means that the chord is 0.25 m, as the span is equal to 1 m. The tail is located at the end of the fuselage. The vertical fin has a NACA 0012 airfoil and the horizontal stabilizer has a NACA 4412, the same used in the wings presented before.

Similarly to what was done for the wing models, it is possible to compare two testing scenarios that correspond to a situation without sideslip and another with a sideslip of 20°. The results are presented in table 3.

	β [°]	F_X $[N]$	F_Y $[N]$	F_Z $[N]$	M_X $[Nm]$	M_Y $[Nm]$	M_Z $[Nm]$
Aircraft model	0	48	0	390	0	15	0
Aircraft model	20	75	24	343	1	14	1

Table 3: Aircraft model aerodynamic forces and moments

3.2.3 Limit Loads and Displacements

The set of results presented before is, as said, a tool to analyse the possible limits of the force balance and to be aware of the order of magnitude of forces and moments to be measured.

Assuming, for both half-wing and aircraft models, an hypothetical situation that results from considering the greatest components of loads and moments of all testing scenarios, it is possible to come up with the worst loading scenario for the half-wing model and for the full aircraft model, both presented in table 4.

	F_X $[N]$	F_Y $[N]$	F_Z $[N]$	M_X $[Nm]$	M_Y $[Nm]$	M_Z $[Nm]$
Half-wing model	213	1171	45	585	115	60
Aircraft model	75	24	390	1	15	1

Table 4: Limit loading situation for the half-wing and aircraft models

Now that the range of maximum expected loads and moments is defined, it is important to guarantee that the force balance does not deform past a certain pre-defined limit. For instance, it is necessary that the point where the model is to be attached does not suffer significant angular displacements as they can induce different aerodynamic angles from the ones that are being tested and, therefore, different aerodynamic loads. These limits have to be defined not only in terms of rotation, but also in terms of translation. The selected limits for angular and linear displacements are represented in table 5.

θ_Y [°]	θ_Z [°]	Linear displacement $[mm]$
0.5	0.5	10

Table 5: Maximum admissible displacements

3.3. Concept Selection

The previous analyses were important to know the range of load values that the force balance has to be able to support. However, there are many types of force balances which application depends on many factors, mainly the testing conditions.

In this specific case, given the fact that the force balance will be used in an academic environment and to test models of different shapes, it is important to guarantee both versatility and simplicity of construction that are only possible to achieve with external balances. In fact, internal balances are greatly dependent on the model shape and for this reason they are not adequate for our purpose. The balance is expected to be used in tests for a wide variety of models, such as wings and scaled planes. There are different types of external force balances and for this reason it is important to analyse and discuss the advantages and disadvantages of each configuration. The most appropriate manner to do so is to carefully compare different existent solutions, highlighting their pros and cons and quantitatively assess some of their main features. Considering six different types of external force balances: platform, rotating-platform, pyramidal, pyramidal-platform and two innovative designs, it is possible to come up with a selection methodology to assess the most suitable option.

3.4. Selection Methodology

The best way to perform this selection analysis is to define categories and requirements and assess each design in each category. These requirements have to meet wind tunnel specifications, testing conditions and guarantee a user-friendly operation.

The use of Analytic Hierarchy Process (AHP) [7] is the best way to gather all the information, evaluate categories and obtain the best solution since it is adequate for complex decision making by reducing them to sets of pairwise comparisons. The decisions are based on both evaluation criteria and types of force balance. The AHP generates a weight for each criterion, based on decision maker's pairwise comparisons, that reflects its importance. Then, for a certain criterion, all of the options are compared and a score is assigned to each option. At the end, the option scores are combined with the criteria weights and the global score for each option is determined. First, it is important to introduce and define the criteria that is going to be considered. It is possible to highlight two main categories: construction and operation that are worth around 40% and 60% in terms of the total force balance assessment.

Regarding construction, among the set of criteria that one can find to be important, there are some of greater relevance: robustness, simplicity, fabrication, instrumentation, structurally adaptable, innovative design and cost.

In a similar manner, when it comes to operation, it is possible to highlight some more important criteria: wind tunnel attachment, support versatility, measurement accuracy, force and moment decoupling and results processing.

Figure 4 shows the final scores of all the considered possibilities of external force balances. It can be seen that the platform force balance presents the maximum score, followed by the rotational-platform. Although the platform balances are very simple, they present a very good commitment in an academic environment due to the simplicity of assembly, operation and maintenance.

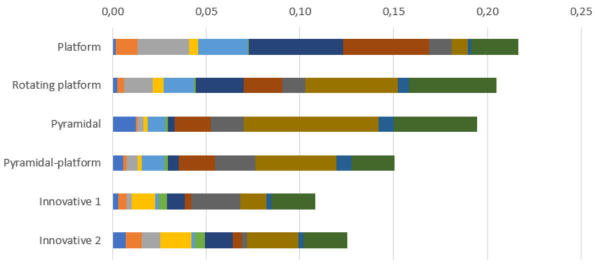

Figure 4: Final AHP score per force balance type

3.5. *Stewart* Platform

In general, platform balances have a main plate (platform) which is connected to the strut where the model is mounted. This platform is supported by bars that are linked to a fixed platform on the floor and are supposed to carry axial forces only. In general terms, we are interested in having six degrees of freedom. To accomplish this, it is necessary to consider six bars that must not be collinear so that the six leg forces can be linearly independent. One of the most known mechanisms is called the *Stewart* platform. Since its appearance, it was used mainly in flight simulators in the training of pilots, although it can be used in many other physical tests. In this case, and provided its good stiffness, it is suggested to be used as a force and moment sensor by instrumenting its elastic legs [4]. *Stewart* platforms may present diverse shapes but the most widely known are designated by 3-3, 3-6 and 6-6, represented in figure 5 [8].

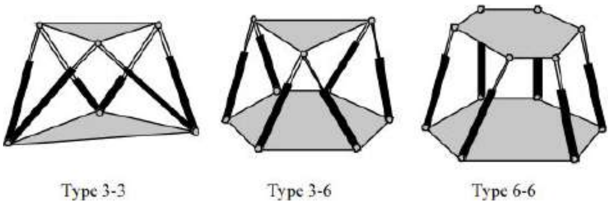

Figure 5: *Stewart* platform types [3]

Although these are the most common designs, some variations may arise to simplify construction or operation. These variations have, however, to be carefully calculated and dimensioned because some configurations may lead to uncontrollable states known as singularities. In the case of a force-moment sensor, when singularities occur it is impossible to balance a certain load applied to the platform. To evaluate the quality of a certain design, it was introduced the quality index (λ), that varies from 0 to 1, being 1 the optimal design and 0 a design with singularities, and is defined as

$$\lambda = \frac{|J|}{|J|_m}, \tag{1}$$

where $|J|$ stands for the determinant of the Jacobian matrix of a certain configuration to be studied and $|J|_m$ stands for the determinant of the Jacobian matrix that corresponds to the optimal configuration. The Jacobian matrix is defined as

$$J = \left[\hat{S}_1 \quad \hat{S}_2 \quad \ldots \quad \hat{S}_n,\right], \tag{2}$$

where n is the number of bars and $\hat{S}_i$ is the unit vector of the Plucker coordinates along the line of the i^{th} bar. As for the vector $\hat{S}_i$, it is defined as

$$\hat{S}_i = \begin{bmatrix} x_2 - x_1 & y_2 - y_1 & z_2 - z_1 & y_1 z_2 - y_2 z_1 & x_2 z_1 - x_1 z_2 & x_1 y_2 - x_2 y_1 \end{bmatrix}. \tag{3}$$

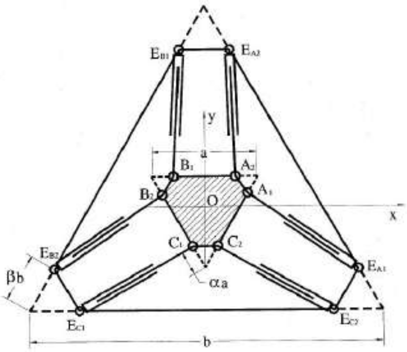

Figure 6: 6-6 *Stewart* platform based on the 3-3 platform

By analysing the relation between the different parameters that define the platform configuration (a, b, α, β, h), which are shown in figure 6 and obtaining the quality factor for different feasible sets of properties, it was possible to get a good configuration without compromise both quality of design and mechanical feasibility. This final configuration is defined by $a = 350mm$, $b = 700mm$, $\alpha a = 60mm$, $\beta b = 45\ mm$ and $h = 300\ mm$ and has a quality index of $\lambda = 0.995$, which is pretty close to the optimal design. The definition of αa and βb instead of α and β, respectively, was due to a thinking forward process: one is interested in having a shape that is the best approximation to a triangle as possible, for the both platforms, as the 3-3 platform is considered to be the most stable design. This forces the connection of the two bars to be as close as possible to the virtual vertex. The values of αa and βb represent, respectively, the trimmed vertices of upper and base platforms and consider the minimum distance between the two connections of the bars to the platforms taking also into account the connection mechanism that will be presented later. The final configuration of this *Stewart* platform is shown in figure 7.

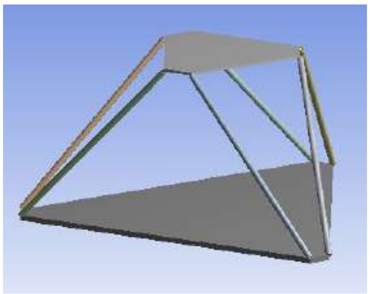

Figure 7: Final *Stewart* platform configuration

4. Mechanical Design

Having defined the general configuration, it is necessary to design each of the components, determining their exact dimensions and the materials to be used, so they can be manufactured or purchased. The force balance is constituted by two platforms connected by means of bars that have to deform and carry loads only in the axial direction. A strut will also be needed to mount the model to be tested as well as a mechanism to fix it to the upper platform. Two different struts, one to test half wing models and another to test full plane models, will be considered. Additional mechanisms will be design to guarantee that the force balance is fully operational. The preliminary model of the force balance is shown in figure 8, to test aircraft models (figure 8(a)) and half wing models (figure 8(b)).

(a) Aircraft testing (b) Half wing testing

Figure 8: Preliminary model of the force balance

In order to analyse the model subjected to the expected operation conditions, finite element analysis will be performed using *SolidWorks*, v2017. In terms of element type and considering the use of a high-quality mesh, parabolic tetrahedral solid elements will be used to discretize the domain adopting a curvature-based mesher that will automatically refine the mesh near the curves and edges of the structure. These elements are defined by four corner nodes, six mid-side nodes, and six edges.

4.1. Sizing and Material Selection

In the following sections, a number is assigned to each component that is being described. This number corresponds to the caption of the figure 12 where each of the numbers is pointing at the respective component.

4.1.1 Strut and Flange

In terms of design, the strut (10) consists of a metallic bar that connects the model that is positioned in the center of the test section to the force balance structure and, for this reason, it is necessary to guarantee that the strut has an appropriate height.

Since this strut will be placed in the test section, it will also be subjected to the flow forces and, for this reason, it is important to guarantee that the surface area of the strut crossed by the airflow is minimum. The best way to guarantee this is to use a bar with a relatively small diameter. On the other hand, forces and moments will be applied in the attachment point that is the top of the strut and it is necessary to keep the rotation of the strut below certain predefined values and thus limiting torsion and bending behaviour of the strut. This is achieved by modifying the shape of both strut and flange (9) which consists of a metallic disc that connects the strut and the moving platform.

An extensive analysis was performed to assess the effect of changing the shape of both strut and flange. For the strut, cross-sections with different internal and external diameters were considered and for the flange a different design with smoother edges was evaluated. The final strut presents a cross section with an external diameter of $32\,mm$ and an internal diameter of $20\,mm$ and a height of $400\,mm$ when used to test aircraft models and $130\,mm$ when used to test half-wing models, vertically.

4.1.2 Fixed platform

Starting with the fixed platform (1) at the bottom of the structure, the main aspects one needs to consider are the platform thickness and the location of the holes to mount the rod end bearings couplers and the sideslip angle adjustment mechanism.

Concerning the thickness of the platform, it has to be significant since it is also going to help providing support of the whole structure. As for the material, steel was found to be the best option. Giving its average density (around $7860\ kg/m^3$) and the desired shape, it is possible to relate the mass of the fixed platform with its thickness: considering a thickness of $10\,mm$, the weight of this platform is found to be around $16.4\,kg$. The *3D* model of this platform is represented in figure 9.

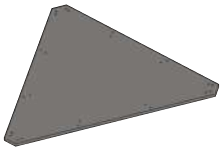

Figure 9: *3D* model of the fixed platform

Considering the maximum expected loads and moments and a specific type of structural steel (1.0037) for the material, the maximum stress value is slightly below $110\ MPa$ which is below the yield strength ($235\ MPa$).

4.1.3 Sensing Bars and Rod End Bearings

Cylindrical bars (6) will connect both platforms and are supposed to axially carry all the loads. Since the bars present a simple shape, the best solution was to search for the available possibilities in hardware stores. Since it is supposed to measure the deformation of the sensing bars in their axial direction, it is essential to guarantee that the bars will only deform in this way. To do so, rod end bearings will be coupled to both extremities of each bar.

A simultaneous market research on stock aluminium bars and rod end bearings led to choose aluminium bars with $10\,mm$ of outer diameter and $7mm$ of inner diameter, the adequate dimensions to drill the internal M8 screws on both extremities for the selected rod end bearings with male threads. To guarantee a more efficient assembly of the bearings in the bars, an effective solution was to use different directions for the threads in both extremities, that is, in one of the extremities it is used a rod end bearing with a left male thread, and in the other extremity it is used an equivalent rod end bearing with a right male thread, being the internal threads in the bars done accordingly. The selected rod end bearing is represented in figure 10.

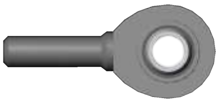

Figure 10: Rod end bearing

This specific type of rod end bearing (3,5) is capable of support a maximum dynamic load (C_r) of $5850N$ and a maximum static load (C_{0r}) of $12900N$. As referred previously, the maximum normal stress of the bar is important as this value can be used to obtain the maximum axial force value and compare it to the rod end bearing specifications. Considering the cross section area of the bar and the stress value, and using the expression $\sigma = \frac{F}{A}$, one can obtain the results depicted in table 4.1.3.

Normal Stress (σ) [Pa]	Cross-section area [m^2]	Axial force [N]
2.373×10^7	1.60×10^{-4}	3802

Table 6: Rod end bearing integrity

4.1.4 Moving Platform

The moving platform (4) consists of a sandwich panel with a hard foam core and face sheets of a carbon fibre composite. The core provides light-weight structural integrity while the carbon fibre/epoxy faces provide both high stiffness and strength. It is very similar to the fixed platform described previously and, for this reason, its design will also be similar. The stress distribution in this component is shown in figure 11.

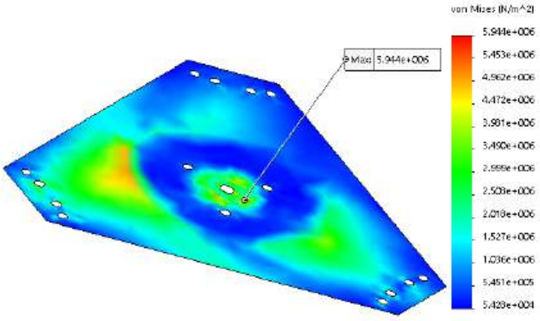

Figure 11: Stress distribution in the moving platform

4.1.5 Coupler

In order to link the sensing bars and the rod end bearings to both platforms, a metallic coupler (2) was projected. This metallic piece will be screwed to the platforms and the rod end bearing will be attached to it by means of steel rods and breaks. This link mechanism will be made of steel, like the base platform, by bending a sheet metal into a U-shaped piece with a thickness of 3 mm. The simulation shown a maximum stress value of 110.2 MPa, which is considerably below the value of yield strength for the considered alloy steel ($\sigma_Y = 620\ MPa$).

4.1.6 Sideslip Angle Adjustment: Rotating Platform

It necessary to implement a mechanism that allows the user to choose the adequate sideslip angle to the experiment. A rotating mechanism (7) will be attached to a fixed rectangular shaped 10 mm thick steel plate (8) which, in turn, will be connected to the ground. The maximum stress (74.88 MPa) occurs in the vicinity of the holes that connect the rotary collar to the force balance structure itself, however this value is below the yield strength of the aluminium alloy that the rotary collar is made of ($\sigma_Y = 325\ MPa$) and the steel that composes the table ($\sigma_Y = 235\ MPa$).

4.1.7 Angle of Attack Adjustment

In order to adjust the angle of attack, a new mechanism has to be designed. The setting of α will be conducted at the top extremity of the force balance by means of an adjustable hook. At the top of a strut, a U-shaped metallic support will be welded (11). Another similar metallic component (12) will be attached to it by means of bolted connections which can be adjusted and tighten to the desired angle of attack. This piece is made of aluminium Al 2024-T4 that has a yield strength of 325 MPa and which is above the maximum value of stress in the mechanism (around 5.75 MPa).

4.1.8 Complete Assembly

Figure 12 shows the exploded view of the whole structure of the force balance and the set of identifying numbers that were presented throughout the last sections for each component.

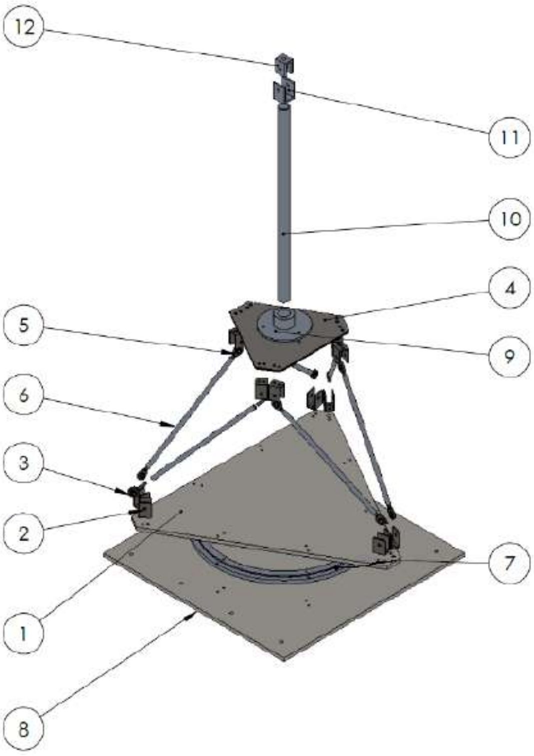

Figure 12: Exploded view of the force balance model and identification of its components

5. Instrumentation

After having designed and dimensioned all the mechanical parts of the force balance, it is important to select the sensors that have to be attached to the mechanism in order to determine the loading conditions.

The following strain gauge was selected: **1-LY13-6/350** by HBM. The first digits *1-LY1* refer to the type of extensometer, in this case L stands for linear, Y stand for universal foil strain gauges for stress analysis and *1* stand for the type of wiring in this case with leads beneath the measurement grid. The next digit *3* refers to the material in which the extensometer is supposed to be attached, in this case aluminium. The last two numbers *6* and *350* represent, respectively, the measuring grid length, in milimeters, and the nominal resistance, in Ω. These strain gages can have a maximum elongation (ϵ_{max}) of $50000\,\mu m/m$, that is 5×10^{-2}, and so it must be guaranteed that, for all the critical loading conditions presented previously, the sensing bars do not deform (both axially and tangentially) past this value of strain. Table 5 proves so by comparing this value to the maximum expected values of strain for the testing conditions.

Maximum micro-strain values (μ)	Axial	Tangential	Maximum Admissible
Plane model	105	34	50000
Half-wing model	395	130	

Table 7: Maximum absolute values of microstrain in the bars for the maximum expected loading conditions

A data acquisition system has to be carefully chosen in order to be compatible with the selected strain gauges. Considering the mounting mechanism of the strain gauges, that are supposed to form *Wheatstone* bridges, one can search for this specification on the available options for data acquisition systems. In fact, there are systems that are specified to receive an input signal directly from *Wheatstone* bridges and then, the output signal is decoded in a computer software, and is possible to read all the deformation associated with each *Wheatstone* bridge. The best solution was found to be a hardware from *National Instruments*™ in particular the board *NI 9237*. It has 4 input channels which means that it is capable of measuring signals from 4 full bridges. Since the force balance has a total of 6 sensing bars, there are also 6 *Wheatstone* bridges. This means that, to fully obtain the loading conditions, it is necessary to have two of these systems of data acquisition.

In addition, to measure the airflow velocity inside the wind tunnel, for each testing condition, a Pitot tube has to be installed and properly calibrated.

6. Manufacturing, Cost and Assembly

6.1. Bill of Materials and Cost Breakdown

Considering all the components presented before, it is possible to come up with an estimated budget for the force balance. Regarding off-the-shelf components, not only mechanical but also electronic, it was possible to research and find the best offers. Concerning all made-to-specification components, several requests of quotation to specialized companies had to be made, in order to obtain the best offers. Table 8 sums up the final cost of each component and the estimated cost of the force balance.

It is possible to conclude that, in terms of cost percentage, the electronic components of the force balance constitute the main slice of the whole project as the data acquisition devices needed to decode the output signals of the strain gauges represent more than 70% of the total cost of the force balance. Overall, one can conclude that this is an expensive project and, for this reason, the assembling and calibration procedures have to be carefully carried out so that the force balance measurements can be as precise as possible.

Table 8: Expected cost for force balance components

	Component	Quantity	Price (€)	%
Mechanical	Table	1	121.52	3.1
	Rotating collar	1	57.58	1.5
	Fixed platform	1	117.86	3.0
	Coupler	12	210.18	5.3
	Rod end bearing (INA GAL(R)8-UK)	12	231.60	5.8
	Sensing bar	6	8.00	0.2
	Moving platform	1	–	–
	Flange[1]	1	15.00	0.4
	Strut[1]	1	8.00	0.2
	α adjustment mechanism	2	139.09	3.5
	Bolts, nuts and other connectors	106	19.25	0.5
	Subtotal		928.08	23.4
Electronic	Strain gauges (HBM 1-LY13-6/350)	24	253.65	6.4
	DAQ NI9237	2	2782.00	70.2
	Subtotal		3035.65	76.6
	Total		3963.73	100

[1] This indicates that the cost is estimated and is based on similar parts.

Table 9: Expected cost for force balance components

6.2. Manufacturing and Assembly Considerations

Regarding the set of parts that will constitute the force balance and starting with the ones that will be made to specification, the table, the fixed platform, the couplers and the mechanism to control the angle of attack are going to be manufactured in the same specialized shop. The table and the fixed platform are made of a steel sheet cut to the desired shape and the couplers and the mechanism to adjust the angle of attack are obtained by bending a sheet metal to the desired shape.

To keep all the components in place and guarantee the force balance integrity, it is necessary to carefully detail the way the components are linked to each other. To connect the components to each other, the main mechanism that will be used used is the bolted connection. Some dowel pins will also be used to connect the rod end bearings to the respective couplers.

7. Calibration

In order to use the force balance, it is necessary to have it fully calibrated. To perform this calibration, it is necessary to select and apply a numerical methodology as well as an adequate calibration facility. Least squares formulation [5] was found to be the better option since it provides good results and is the most widely known as it is easier to comprehend. In fact, this method was found to have optimal statistical properties as it is consistent, unbiased and efficient.

7.1. Calibration Methodology

The overall calibration methodology [6] can be summed up in the following procedures: plan, carefully, each loading condition of the calibration process; apply the desired weights to each tray; register the bridges output; estimate the calibration coefficients matrix; estimate the uncertainties matrices and reiterate; evaluate the fitting.

8. Conclusions

The main goal of this master thesis was to design a force balance to use in the Aerospace Engineering Laboratorys wind tunnel at Instituto Superior Tcnico. In order to adapt it to the dimensions of the wind tunnel and to the possible measuring scenarios, a careful analysis was carried out.

After having defined the load range the force balance has to be able to carry, it was possible to define its main structure. A comparative analysis based on relevant criteria, such as cost, manufacturing simplicity or measurement accuracy, was performed in order to find the most suitable layout for this application. This analysis along with further research revealed that a *Stewart* platform-based force balance was the best option.

Combining the two main structural aspects stated above (load range of operation and force balance layout), it was possible to mechanically design all the components of the force balance. This mechanical analysis had to take into account several aspects, like the weight of the structure, the manufacturing easiness of the components, the maintenance simplicity of the parts and the assembly of the whole structure, but always keeping the overall budget as low as possible.

Having established the mechanical structure of the force balance and guaranteed its integrity when the maximum expected loads are applied, it was necessary to fully instrument it so that the applied forces and moments can be quantified, by measuring the deformation of the structure. To do so, specific strain gauges and data acquisition system were selected and an installation scheme was presented.

In order to guarantee the accurate correspondence between the applied loads and the sensors measurements, a calibration process has to be carried out so a methodology based on the least squares theory was proposed.

In conclusion, a fully operational force balance concept was designed to be placed in the wind tunnel to test a wide range of models, provided all the components are available.

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