Design and Structural Analysis of Three Component Strain Gauge Balance

Guru Sankar Duppada¹, Nikhil Nalamasu¹, Naga Saikiranmai Aduri¹, Navya Arisetty¹,
Ramakrishna Madhira², Suresh Kumar C³

¹UG Scholar, Department of Aeronautical Engineering, Bharath Institute of Higher Education & Research, Chennai-600073, India.

²Assistant Professor, Department of Aeronautical Engineering, Bharath Institute of Higher Education & Research, Chennai-600073, India.

³Associate Professor, Department of Aeronautical Engineering, Bharath Institute of Higher Education & Research, Chennai-600073, India.

Abstract

Strain gauge balances are used to measure the aerodynamic forces that are acting on a scaled models or prototypes of different aerodynamic shapes. In this competitive world, to evaluate the reliability of the structure a costless attempt is made by simulating (Ansys) the balance under various conditions and forces. Three component internal strain gauge balance is confined with the measurement of lift, drag and pitching moment. The loads that are acting on the body is measured in the form of strain by strain gauges. This paper provides the information related to the installation of strain gauges, design of beam according to the wind tunnel dimensions, and analyzing the structure by simulation of the beam with two different materials. The results are thus compared with the theoretical results that are calculated.

Keywords - Drag, Lift, Pitching moment, Proto-type Strain gauge, Strain gauge balance, Wind tunnel

Review of Literature

Mssrigarom@ntu.edu.sg The principle that is used in the strain gauge balances is bending-beam principle. The forces acting on the balance causes strain on its surface, which will be measured by the strain gauges.

Ribeiro et al. The strain gauges are attached in wheatstone bridge configuration in which the change in strain will cause the change in resistance of the resistance and can be measured with data acquisition system.

Bokai Liu et al. In order to simulate the performance of the aircraft better, we need to simulate the aircraft in a wind tunnel. Current internal strain gauge balances are mounted inside the model that causes a change in the structure. So the structure can be mounted at the tail of the structure. So it can also make ease for calculating the torque.

Y.-J.Shi et al. The strain due to the axial forces is very small. To measure the axial forces thwart 1t beam is made and was improved using the optimization with FEA software. The beam reduces the Y-interaction on X availability, benefiting the stability improvement of axial force.

Marco Scipioni et al. Internal balances vary in size and load carrying capacity, but in general they can be briefly categorized either by Force and moment balances

J.W.Hou et al. Elastic beam theory beam deformation is the result of two components, internal shear force and bending moment. The largest contributor to deformation in an elastic beam is due to bending, when the ratio of beam length to beam depth (L/D) is very large, i.e greater than 10:1. The deformation effects due to shear will be negligible and if the beam length to beam depth (L/D) is less than 10:1, then the Timoshenko Beam Theory (TBT) provides a more accurate results of deformation.

1. INTRODUCTION

Internal Strain gauge balance can be used most frequently in a stand to calibrate the aerodynamic forces and moments on a test model (in a test section). An important thing of a balance to be used is monitoring and extracting the forces and moments with less efforts. Either the flow may be steady or fluctuating, it is possible to extract the required results to evaluate the loads on the model, using stain gauge balances. These balance types are generally differentiated based on the number of force/moment that are extracted using the balance and the way the balance is being mounted. If they are mounted inside the model they are referred as internal balances and if they are mounted outside of the model or the wint tunnel they are referred as external balances. Here we consider internal strain gauge balances.

Generally the coordinate system is formed in the wind tunnel to evaluate the flow direction and forces. In normal, lift is defined as the force vertical or perpendicular to the flow direction, whereas the drag is termed as the force in the direction of the flow. Pitching moment is considered with the force that tends the body to the right of y axis. As we designed the structure to be three component internal strain gauge balance, it is confined to only lift (normal force), drag (axial force) and the pitching moment.

Axis system	component
X axis	Drag or axial force
Y axis	Lift or normal force
Z axis	Pitching moment

1.1 Strain gauge

Strain gauge are the sensors based on electrical resistance which generates a variation in its electrical resistance when subjected to an external force/deformation in its length. It is used to measure strain on a object.

1.1 Purpose

It is very challenging to evaluate the results from the tested aerodynamic model in the wind-tunnel. Although we got the readings we are not sure about the accuracy. The costliest phase of production is testing.

The emphasis made to design and analyze a three component internal strain gauge balance is to measure the forces and moment of an aerodynamic model mounted in the wind-tunnel. The beam calibrates lift, drag and pitching moment due to fluctuations in the fluid flow over a model. To maintain the cost efficiency designed beam is simulated and the results are analyzed

2 .MATERIALS AND PROPERTIES USED

1. Aluminium
 - Youngs modulus = 71.1Gpa
 - Poissons ratio = 0.3
 - Shear modulus = $2.4 \times 10^{10} \text{N/m}^2$
2. Steel
 - youngs modulus – 210Gpa
 - Poissons ratio = 0.3
 - Shear modulus = $7.2 \times 10^{10} \text{N/m}^2$

3. STAGES OF WORK

1. Design of beam
2. Uni-directional loading
 - 2.1. When beam is subjected to lift
 - 2.2. When beam is subjected to drag
 - 2.3. When beam is subjected to pitching moment
3. Bi-directional loading
 - 3.1. When beam is subjected to lift and drag
 - 3.2. When beam is subjected to lift and pitching moment
 - 3.3. When beam is subjected to drag and pitching moment
4. Tri-directional loading
 - 4.1. When subjected to lift , drag and pitching moment

3.1 Design of beam

3 component internal strain gauge balance is to measure lift, drag and pitching moment. The beams is designed by refereeing various journals and previous work.

3.1.1 Design Parameters

- Selected cantilever beam with a circular cross section of Dia **1.5cm** and length **30cm** and there will be two square sections with **8mm** side. By mounting the beam in wind tunnel, fixing it to the model and allow the flow then we can measure the aerodynamic forces such as lift, drag and pitching moment through the strain Gauge attached to the beam's square portion.
- Incentive of circular cross section of a beam is to extract the pitching moment value. The screws on the beam is to mount the models. The strain gauges are attached on the square or rectangular cross sections rather than circular section due to circumvent the more errors and extract nearly exact results and also to avoid more percent of error with strain gauges.
- The wires will be connect to the beam directly passed to DAQ. To extract the results and to avoid maximum errors in calculations.
- Beam is designed to withhold minimum load of 100 grams and it can be capable of extracting the required forces for any Aerodynamic model.

Fig 1 Design of beam in catia

Fig 2 Three view diagram of beam

Fig 3 Design of beam with dimensions

Structural Analysis

Beam is subjected to various loads, forces and moments to evaluate the strength of the beam. It is tested with two different materials aluminium and steel. Theoretical results are also calculated along with the simulation results to get a comparison.

SIMULATION RESULTS

4 UNI DIRECTIONAL LOADING OF BEAM

4.1 When subjected to only lift force

Fig 4 Aluminum beam subjected to 100N lift at free end

Fig 5 Steel beam subjected to 100N lift at free end

Table 1 Simulation results of different loads of lift

Lift (n)	Aluminium deflection (m)	Steel deflection (m)
1	0.00014	0.00005
10	0.0014	0.0005
20	0.0028	0.001
30	0.0042	0.001
40	0.0056	0.002
50	0.0070	0.0025
60	0.0084	0.003
70	0.0098	0.0035
80	0.011	0.004
90	0.012622	0.0045031
100	0.014024	0.0050035
110	0.015426	0.0055038
120	0.016829	0.0060042
130	0.018231	0.0065045
140	0.019634	0.0070049
150	0.021036	0.0075052
200	0.028048	0.010007
250	0.03506	0.012509
300	0.042072	0.01501

4.2 When subjected to drag

Fig 6 Aluminium beam subjected to 150N drag

Fig 7 steel beam subjected to 150N drag

Table 2 Simulation results of different loads of drag

Drag (N)	Aluminium deflection (m)	Steel deflection(m)
5	0.000028	0.00000997
50	0.00028	0.0000997
100	0.00056	0.000199
150	0.00084	0.000299
200	0.00112	0.000399
250	0.0014	0.000498
300	0.00168	0.000598

4.3 Torsional analysis or when subjected to pitching moment

Fig 8 Steel beam subjected to torque of 10 Nm in anticlockwise direction

Fig 9 Aluminium beam subjected to torque of 10 Nm in anticlockwise direction

Table 3 Simulation results of different torque loading conditions

Torque(Nm)	Aluminium deflection(m)	Steel deflection(m)
2	0.00011	0.00004
4	0.000233	0.00008
6	0.00035	0.00012
8	0.00046	0.000162
10	0.00058	0.0002

5. COMBINED LOADING

5.1 When the beam is subjected to lift and drag

Fig 10 Steel beam with drag of 150N and lift of 150N

Fig 11 Aluminium beam Loaded under drag of 150N and lift of 150N

Table 4 Simulation results of different lift and drag loading conditions

Loading in drag direction (N)	Loading in lift direction (N)	Aluminium deflection (M)	Steel deflection (M)
5	5	0.001	0.00036
5	150	0.021	0.0077
5	300	0.043	0.0154
50	5	0.072	0.0025
150	5	0.021	0.0076
150	150	0.0306	0.01
150	300	0.0486	0.0176
300	5	0.0429	0.0152
300	150	0.048	0.0171
300	300	0.0613	0.0218

Fig 12 Graphical representation of aluminium beam subjected to lift/ drag of various conditions

Fig 13 Graphical representation of steel beam subjected to lift/ drag of various conditions

Fig 17 Aluminium beam subjected to torque of 10Nm and transverse load of 300N

5.2 Loading under pitching moment and lift

Fig 14 Steel beam subjected to pitching moment 10Nm and lift of 150N

Fig 15 Aluminium beam subjected to pitching moment 10Nm and lift of 150N

5.2.1 Stress analysis

Stress is a very crucial factor in consideration of failure so the stress analysis is also been made

Fig 16 Steel beam subjected to torque of 10Nm and transverse load of 300N

Table 5 Simulated stress results when different loads of lift and pitching moment is acted

Pitching moment (Nm)	Lift (N)	Steel beam stress (N/m ²) (1*10 ⁷)	Aluminium beam stress(N/m ²) (1*10 ⁷)
2	5	3.57	3.57
2	150	51.7	51.6
2	300	103	103
6	5	9.99	10
6	150	52.1	52
6	300	103	103
10	5	1.66	1.66
10	150	52.5	52.4
10	300	104	1.03

Table 6 Simulated deformation results when subjected to different loads of lift and pitching moment

Pitching moment (Nm)	Lift(N)	Deflection steel(m)	Deflection aluminum (m)
2	5	0.00029	0.00083
2	150	0.0077	0.021
2	300	0.0154	0.043
6	5	0.00037	0.001
6	150	0.0077	0.0219
6	300	0.0154	0.0435
10	5	0.0004	0.00128
10	150	0.0078	0.022
10	300	0.0155	0.044

Fig 18 Plot of steel beam subjected to lift and pitching moment against deflection

Fig 19 Plot of aluminium beam subjected to lift and pitching moment against deflection

5.3.1 Stress analysis

Fig 22 stress of aluminium beam subjected to 300N drag and pitching moment of 10Nm

Fig 23 stress of steel beam subjected to 300N drag and pitching moment of 10Nm

Table 7 Simulated results of beam when different loads of drag and pitching moment is acted

Pitching moment(N m)	Drag (N)	Steel deflection(m)	Stress (1×10^7)(N /m ²)	Al deflection (m)	Stress (1×10^7)(N/m ²)
2	5	0.00005	3.3	0.00014	3.3
2	150	0.00033	29.6	0.00095	29.5
2	300	0.00063	59.3	0.00179	58.9
6	5	0.00013	9.99	0.00037	9.99
6	150	0.00041	29.7	0.00118	29.5
6	300	0.00071	59.4	0.002	59
10	5	0.00021	16.6	0.00061	16.6
10	150	0.0005	29.8	0.00142	29.6
10	300	0.00079	59.4	0.0022	59

5.3 Beam subjected to pitching moment and drag

Fig 20 Deflection of Aluminium beam subjected to 150N drag and pitching moment of 10Nm

Fig 21 Deflection of steel beam subjected to 150N drag and pitching moment of 10Nm

Fig 24 plot of steel beam subjected to drag and pitching moment against deflection

Fig 25 plot of steel beam subjected to drag and pitching moment against deflection

Fig 26 plot of stress analysis of steel beam subjected to drag and pitching moment against deflection

5.4 when subjected to lift, drag ,pitching moment

Fig 27 Deflection of aluminium beam subjected to lift 150N , drag 150N and pitching moment of 10Nm

Fig 28 Deflection of steel beam subjected to lift 150N , drag 150N and pitching moment of 10Nm

5.4.1 Stress analysis

Fig 29 Stress of aluminium beam subjected to lift 300N , drag 300N and pitching moment of 10Nm

Table 8 The simulated results of beam when subjected to different loads of lift , drag and pitching moment

Drag(N)	Lift(N)	Moment (Nm)	Aluminium deflection(m)	Aluminium stress(N/m ²)(1*10 ⁷)	Steel deflection(m)	Steel stress(N/m ²)(1*10 ⁷)
5	5	2	0.0008	3.57	0.000295	3.57
5	150	2	0.021	51.7	0.00772	51.8
5	300	2	0.043	103	0.0154	103
150	5	2	0.0013	29.5	0.000437	29.7
150	150	2	0.021	53.6	0.00773	53.6
150	300	2	0.043	105	0.0154	105

Drag(N)	Lift(N)	Moment (Nm)	Aluminium deflection(m)	Aluminium stress(N/m ²)(1*10 ⁷)	Steel deflection(m)	Steel stress(N/m ²)(1*10 ⁷)
300	5	2	0.0019	59	0.00069	59.4
300	150	2	0.021	66.5	0.0077	66.9
300	300	2	0.043	107	0.0154	107
5	5	6	0.001	9.99	0.00037	9.99
5	150	6	0.021	52.1	0.00779	52.2
5	300	6	0.043	104	0.0154	104
150	5	6	0.0014	29.6	0.00051	29.8
150	150	6	0.021	54	0.0078	54
150	300	6	0.043	105	0.01549	106
300	5	6	0.002	59.1	0.00077	59.4
300	150	6	0.02	66.2	0.00783	66.6
300	300	6	0.043	107	0.0155	107
5	5	10	0.001	16.6	0.00045	16.6
5	150	10	0.022	52.6	0.00787	52.6
5	300	10	0.043	104	0.0155	104
150	5	10	0.0016	29.6	0.00059	29.8
150	150	10	0.022	54.4	0.00789	54.4
150	300	10	0.043	106	0.0155	106
300	5	10	0.002	59.1	0.00085	59.5
300	150	10	0.023	66	0.0079	66.4
300	300	10	0.0438	108	0.0155	108

pitching moment against deflection

Fig

31 plot of aluminium beam subjected to lift, drag and

Fig 32 plot of steel beam subjected to lift, drag and pitching moment against deflection

Fig 33 plot of stress analysis of beam when subjected to lift , drag and pitching moment

THEORITICAL RESULTS

6. UNI DIRECTONAL LOADING

6.1 When subjected to only lift

$$D = 15\text{mm} = 1.5 \times 10^{-2}\text{m}.$$

$$L = 30 \times 10^{-2}\text{m}.$$

$$E = 71.7 \times 10^9 \text{ Pa}$$

First consider circular section of whole beam as one

To find moment of Inertia of circular section

$$I_c = \frac{\pi r^4}{4} = \frac{\pi (0.75 \times 10^{-2})^4}{4}$$

$$I_c = 0.2485 \times 10^{-8} \text{ m}^4$$

Next consider the square section which is 0.8cm*0.8cm

To find moment of Inertia for square section

$$I_{sq} = \frac{bd^3}{12} + \frac{db^3}{12}$$

$$= \frac{0.8^4}{12} + \frac{0.8^4}{12} = 0.0682 \times 10^{-8} \text{ m}^4$$

There are two square sections in the beam with same dimensions.

$$I_{sq} = 2 \times 0.0682 \times 10^{-8} = 0.1365 \times 10^{-8} \text{ m}^4$$

Next considering two screws and calculate its moment of inertia

$$I_{sc} = \frac{0.3 \times 0.4^3}{12} + \frac{0.4 \times 0.3^3}{12} = 0.0025 \times 10^{-8} \text{ m}^4$$

$$I_{sc} = 2 \times 0.0025 \times 10^{-8} = 0.005 \times 10^{-8} \text{ m}^4$$

$$I = I_c - I_{sq} - I_{sc}$$

$$I = (0.2485 \times 10^{-8}) - (0.0682 \times 10^{-8}) - (0.0682 \times 10^{-8})$$

$$I = 0.10697 \times 10^{-8} \text{ m}^4$$

For, $w = 10\text{kg}$ or 100N

$$\delta = \frac{wl^3}{3EI}$$

$$\delta = 11.73 \text{ mm}$$

Similarly the theatrical calculations are made for each loads starting from 100gms to 30kg with an interval of 100 gms for aluminium and steel and are tabulated

Table 9 Calculated results when subjected to different loads of lift

Lift (n)	Alluminium deflection (m)	Steel deflection (m)
1	0.00012	0.00004
10	0.0012	0.00041
20	0.0024	0.00082
30	0.0036	0.0012
40	0.0048	0.0016
50	0.0060	0.0020
60	0.0072	0.0024
70	0.0084	0.0028
80	0.0096	0.0032
90	0.010	0.0037
100	0.012	0.0041
110	0.013	0.0045
120	0.014	0.0049
130	0.015	0.0053
140	0.016	0.0057
150	0.018	0.0061
200	0.024	0.0082
250	0.03	0.010
300	0.036	0.012

Fig 34 Plot of simulation and theoritical results of aluminium and steel when subjected to lift

6.2 WHEN SUBJECTED TO DRAG

Deflection of a cantilever beam subjected to axial load of p is (PL/AE)

WHERE,

P = axial load

L = length of the beam

A = area of cross section

E = young's modulus

So beam is divided into 5 sections in which there are 2 equivalent circular cross sections and 2 cuboidal cross sections with same dimensions and a 1 circular cross section.

So total deformation = $(PL_1)/(A_1E) + (PL_2)/(A_1E) + (PL_3)/(A_1E)$

As the load is same through out the beam and the beam is homogeneous

By substituting the beam dimensions in the above formula, we get the formula in terms of p as total deflection = $0.000008P$ for aluminium and for steel the formula is $0.0000028P$

By substituting the respective drag we get the tabulation to be

Table 10

Drag(N)	Steel beam deflection(m)	Aluminium beam deflection(m)
5	0.000014	0.00004
50	0.00014	0.0004
100	0.00028	0.0008
150	0.00042	0.0012
200	0.00056	0.0016
250	0.0007	0.002
300	0.00084	0.0024

Fig 35 Plot of simulation and theoretical results of aluminium and steel when subjected to drag

6.3 WHEN PITCHING MOMENT IS ACTED

In this case we should mainly matter about the angle of twist and the deflection due to torque is so minimal so that we can neglect the deformation due to torque.

Angle of twist = $(TL)/(GJ)$

WHERE ; T = torsion

L = length of beam

G = rigidity modulus

(for aluminium = 26.9 GPa and for steel 77.2Gpa)

J = Polar moment of inertia $(3.14*(d^4))/32$

On substituting the above values

TORSION (Nm)	ANGLE OF TWIST(aluminium) (rad)	ANGLE OF TWIST (STEEL) (rad)
2	0.257	0.179
4	0.514	0.358
6	0.772	0.538
8	1.02	0.717
10	1.28	0.896

7. COMBINED LOADING

7.1 LOADING UNDER LIFT AND DRAG

Now for theatrical case consider a cantilever beam subjected to drag of 5N and lift of 5N

For deflection of a cantilever beam subjected to both axial and longitudinal load

$$\delta = (W/P) (L * (\tan U/U) - L)$$

$$U = L(\sqrt{p/EI})$$

Where p = axial load

W = longitudinal load

L = length of beam

By the above mentioned formula we calculated the deflection of beam with varying longitudinal load and axial load for aluminium and steel

Table 12

DRAG (N)	LIFT (N)	DEFLECTION ALLUMINIUM (m)	DEFLECTION STEEL(m)
5	5	0.0006	0.0002
5	150	0.018	0.0061
5	300	0.036	0.012
150	5	0.00065	0.0002
150	150	0.019	0.0063
150	300	0.039	0.012
300	5	0.0007	0.0002
300	150	0.021	0.0065
300	300	0.042	0.013

Fig 36 Plot of aluminium beam subjected to lift& drag against deflection

Fig 37 Plot of steel beam subjected to lift & drag against deflection

7.2 WHEN PITCHING MOMENT AND LIFT IS ACTED

Here torsion produces angle of twist and the transverse force produces deflection. The deflection due to pitching moment is so small that can be negligible.

By using the given formulas for lift and angle of twist the values are being tabulated.

Table 13 Theoretical results of beam subjected to different loads of lift and pitching moment

Pitching moment (Nm)	Lift (N)	Deflection steel (m)	Deflection aluminium (m)
2	50	0.0020	0.0060
2	150	0.0061	0.018
2	300	0.012	0.036
6	5	0.00020	0.00060
6	150	0.0061	0.018
10	300	0.012	0.036
10	5	0.00020	0.00060
10	150	0.0061	0.018
10	300	0.012	0.036

Pitching moment produces angle of twist and can be inferred from table 11

Fig38 Plot of aluminium beam when subjected to lift and pitching moment against deflection

Fig 39 Plot of steel beam when subjected to lift and pitching moment against deflection

7.3 WHEN LOADED UNDER PITCHING MOMENT AND DRAG

As discussed above , pitching moment produces the angle of twist and a minimal deflection which can be neglected, we can consider the deflection only due to drag. But in this we consider the deflection due to drag and pitching moment. By using the formulas discussed before, theoretical values are calculated and tabulated. (table 14)

Table 14 Calculated results of beam when subjected to different loads of drag and pitching moment

Moment (Nm)	Drag(N)	Deflection of steel beam(m)	Deflection of aluminium beam (m)
2	5	0.00009	0.00028
2	150	0.0005	0.0014
2	300	0.0009	0.0026
6	150	0.00066	0.0019
6	300	0.0012	0.0036
10	5	0.00042	0.0012
10	150	0.0008	0.0024
10	300	0.0012	0.0036

angle of twist that is produced by the pitching moment can be inferred from table 11

Fig 40 Plot of aluminium beam subjected to pitching moment and drag against deflection

Fig 41 Plot of steel beam subjected to pitching moment and drag against deflection

7.4 When lift , drag and pitching moment is acted

As discussed above , pitching moment produces the angle of twist and a minimal deflection which can be neglected, we can consider the deflection only due to lift and drag. But in this we consider the deflection due to lift ,drag and pitching moment. By using the formulas discussed before, theoretical values are calculated and tabulated.

Table 15

Drag (N)	Lift (N)	Moment (Nm)	Deflection of aluminium beam(m)	Deflection of steel beam(m)
5	5	2	0.00084	0.00028
5	150	2	0.018	0.0062
5	300	2	0.036	0.012
150	5	2	0.00082	0.00029
150	150	2	0.019	0.0064
150	300	2	0.039	0.012
300	5	2	0.00094	0.00029
300	150	2	0.021	0.0065
300	300	2	0.042	0.013
5	5	6	0.0013	0.00045
5	150	6	0.018	0.0064
5	300	6	0.037	0.012
150	5	6	0.0013	0.00045
150	150	6	0.020	0.0065
150	300	6	0.039	0.012
300	5	6	0.0014	0.00046
300	150	6	0.021	0.0067
300	300	6	0.043	0.013
5	5	10	0.0018	0.00061
5	150	10	0.019	0.0065
5	300	10	0.037	0.012
150	5	10	0.0018	0.00062
150	150	10	0.020	0.0067
150	300	10	0.040	0.013
300	5	10	0.0019	0.00062
300	150	10	0.022	0.0069
300	300	10	0.043	0.013

The angle of twist produced by the pitching moment is inferred from table 11

Fig 42 Plot of aluminium beam subjected to lift, drag and pitching moment against deflection

Fig 43 Plot of aluminium beam subjected to lift, drag and pitching moment against deflection

8. MESH INDEPENDENCE TEST

We had conducted a mesh independence test to know whether the simulation depends on type of mesh we use. For better accuracy we mesh should be independent

Fig 44 mesh independence test

Conclusion

We had concluded that the steel beam is more efficient than the aluminium beam. As per our simulation results the beam with the mentioned dimensions well suit for the design of 3 component strain gauge balance. The further work is conserved with the fabrication of balance that is capable of sensing minimum of 100gms weight.

10. References

- [1] Design and development of a three component strain gauge wind tunnel balance by Frederik Francois Pieterse
- [2] J.W.Hou , S.L.Twu : optimum design of internal strain gauge balance : June 2017 :Vol 109/257
- [3] Milan tomin, marco scipioni, Benjamin gatti-Design, construction testing and of three component force balance for educational wind tunnel in undergraduate aerodynamics – 2020 – 29
- [4] Strain gauge Balance Lloyd R. Jenkinson, James F. MarchmanIII, in Aircraft Design Projects, 2003
- [5] Thierry Alonso, Gregory Chagnon- Strain gauge based 3D shape monitoring of beam structures using finite width gauge model – HAL Id: hal-02017091 - 2019