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Design, Optimization and Calibration of 6-Component External Wind Tunnel Balance

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Abstract— A six component platform balance was designed and fabricated in the dept. of Aerospace Engineering, IISc, Bangalore, for measuring aerodynamic forces and moments on models. This balance utilizes load cells for transducing forces into electrical signals. The platform balance consists of a leveled platform constrained by six load cells for measuring forces in vertical, axial and sideward directions. The present work includes the detailed study of wind tunnel balance types, design concepts, the derivation for calibration, transformation and user matrices and establishing the calibration procedure to existing 6-component platform balance at IISc open circuit wind tunnel.

The work also includes FEM analysis of 6-component external force balance, optimization of force measuring elements .To study the static and dynamic coupling of balance when model is attached to force balance by studying individual and coupled behavior and finally Validating the dynamic characteristics in wind tunnel for a typical model and study the error in responses of individual components with increased loads. The present study uses the CATIA to modeling the force balance configuration, Finite Element Analysis (FEA) to find forces developed in the load cells and optimization of force measuring elements. MATLAB is used during the generation of calibration, transformation and user matrices.

Index Terms—Wind tunnel, external balance, platform, 6 componets, aerodynamic, force and moments, load cells, optimization and calibration,

1 INTRODUCTION

The aim of wind tunnel tests is to simulate the flow around bodies or their scaled models. In aeronautical applications, the measurement of aerodynamic loads in a wind tunnel, forces and momentums, is a very difficult task due to the required accuracy. The wind tunnel balances, comprised by several hardware and software components [1], provides directly the pursued measurements, with high accuracy and reliability. Balance types are distinguished by the number of force/moment components which are measured simultaneously one to six are possible and the location at which they are placed [2]. If they are placed inside the model they are referred to as internal balances and if they are located outside of the model or the wind tunnel, they are referred to as external balances. The primary parameters which affect the accuracy of the data are flow quality [3], interference due to model support systems [4], constrains imposed by wind tunnel wall [5], model deformations i.e. changes in the shape of a wind tunnel model under aerodynamic load, can cause the differences between acquired and expected wind tunnel results if the expected results are based on rigid body assumptions [6], model vibrations also pose a threat to the safety of the wind tunnel instrumentation. Motivation for this work is failure of a six-component external force balance during testing due to overloading; the failure was due to the negligence of dynamic forces coming over the balance during the testing conditions. Best to our knowledge, we did not find any studies in literature which investigate the effect of dynamic forces on balance and support system. A systematic study was then proposed to investigate the dynamic forces effects during wind tunnel testing.

2 PLATFORM BALANCE DESCRIPTION

A six-component platform balance was designed and fabricated in the dept. of Aerospace Engineering, IISc, Bangalore, for measuring aerodynamic forces and moments on models. This balance utilizes load cells for transducing forces into electrical signals. The platform balance consists a leveled platform constrained by six load cells for measuring forces in vertical, axial and sideward directions. Fig.1 (a) to Fig.1 (d) shows the different views of the balance. In fig.1 (a) two load cells (H1, H2) are indicated which were used for measuring side force and yawing moment. In fig.1 (b) one load cell (H3) is indicated to measure axial force. In fig.1(c) three load cells (V1, V2, and V3) are fixed to measure normal force, rolling moment and pitching moment. In fig.1 (d) all the six load cells are fixed to form the complete platform balance system.

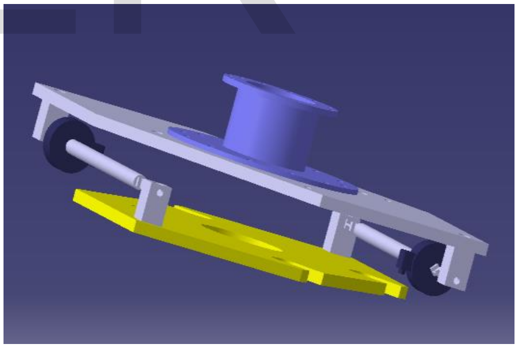

Fig.1 (a)

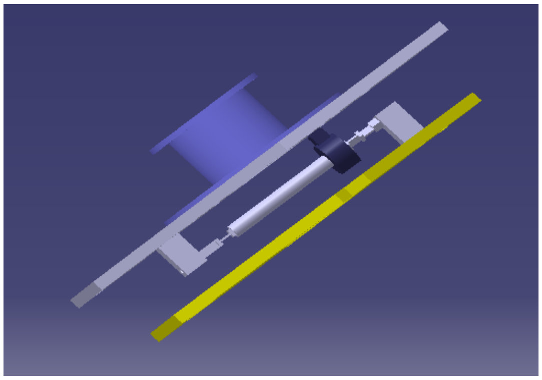

Fig. 1 (b)

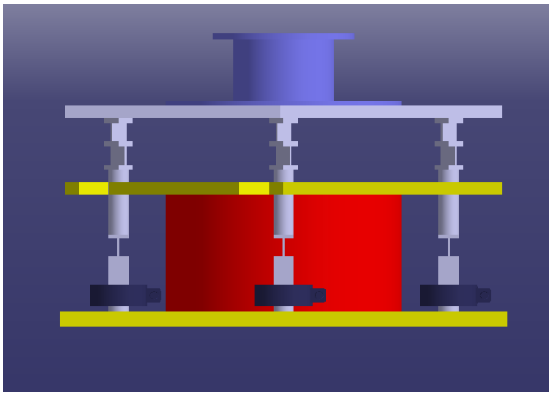

Fig.1 (c)

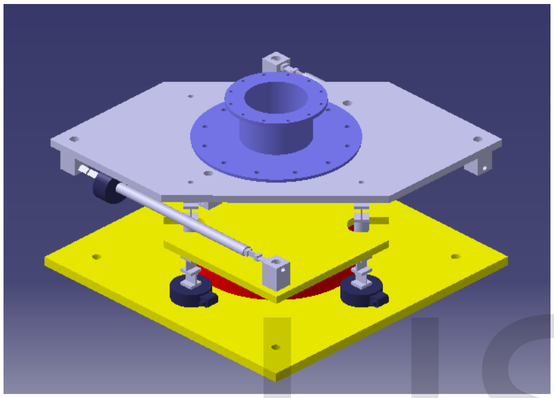

Fig.1 (d)

Figure1. Different views of platform balance

A hexagonal shaped rigid plate (Fig.1 (d)) is used as the metric platform. A circular flange fitting is bolted at the center of this platform (Fig.1 (d)) for the purpose of fixing the model support adopter. The center of the flange coincides with the vertical center line of the platform balance

The vertical components of the load on the model are sensed by the three load cells fitted vertically as indicated in the Fig.1(c). These loads cells are designated as V1, V2 and V3. For sensing side force and yawing moment, there are two load cells fitted horizontally. In the same plane for sensing axial force one load cell is provided. These load cells are designated as H1, H2 and H3. From these six load cells the six-components of forces and moments are obtained. With the direction of axial force aligned parallel to the tunnel axis, we have the following main components referred to the balance Centre.

1. Normal Force (Nf) = V1+V2 +V3
2. Rolling Moment (Rm) = (V1-V2) *a
3. Pitching Moment (Pm) = V3*a
4. Side Force (Sf) = H1+H2
5. Yawing Moment (Ym) = (H1-H2) *b
6. Axial Force (Af) = H3

Where “a” and “b” are the corresponding length of the moment arm.

Table 1. Rating of the balance.

Axial force	136 kg
Side force	250 kg
Normal force	700 kg
Rolling moment	200 kgm
Pitching moment	50 kgm
Yawing moment	70 kgm

3 BALANCE CALIBRATION EXPERIMENTAL DATA AND ERRORS

Table2. Calibration data (1)

Applied Load Nf (kg)	Measured Load (kg)	% Error
-20	-20.0185	-0.0925
-40	-40.011	-0.0275
-60	-59.9901	0.0165
-80	-79.9745	0.03187
-100	-99.9979	0.0021
-80	-79.9745	0.00337
-60	-59.9925	0.0125
-40	-40.0086	0.0215
-20	-19.9924	0.038

Table 3. Calibration data (2)

Applied load Af (Kg)	Measured Load (kg)	% Error
-5	-5.0072	-0.144
-10	-9.9546	0.454
-15	-14.9527	0.3153
-20	-19.8777	0.6115
-25	-24.9131	0.3476
-30	-29.853	0.49
-25	-25.2144	-0.858
-20	-20.2068	-1.034
-15	-15.0998	-0.665
-10	-10.049	-0.49
-5	-5.0138	-0.276

Table 4. Calibration data (3)

Applied moment (PM)(kg-m)	Measured moment (kg-mm)	% error
1.2	1.1882	0.9833
2.4	2.3997	0.0125
3.6	3.6198	-0.55
4.8	4.8037	-0.0771
6	6.0227	-0.3783
4.8	4.8202	-0.4208
3.6	3.6155	-0.4306
2.4	2.4208	-0.8667
1.2	1.1992	0.0667

Table 5. Calibration data (4)

Applied Load (RM)(kg-m)	Measured load (kg-m)	% Error
10	10.0333	-0.333
20	19.933	0.335
30	29.9616	0.128
40	39.9879	0.0302
50	49.8957	0.2086
40	40.1149	-0.2872
30	30.1812	-0.604
20	20.0187	-0.0935
10	9.9803	0.197

Table 6. Calibration data (5)

Applied Load (Sf)(kg)	Measured Load (kg)	% error
10	10.0333	-0.333
20	19.933	0.335
30	29.9616	0.128
40	39.9879	0.0302
50	49.8957	0.2086
40	40.1149	-0.2872
30	30.1812	-0.604
20	20.0187	-0.0935
10	9.9803	0.197

Table 7. Calibration data (6)

Applied moment (Ym)(kg-mm)	Measured moment (kg-mm)	% error
-2	-1.9638	1.81
-4	-3.934	1.65
-6	-5.9076	1.54
-8	-7.8926	1.3425
-6	-5.9025	1.625
-4	-3.9642	0.895
-2	-1.9769	1.155

4 CALIBRATION CURVES

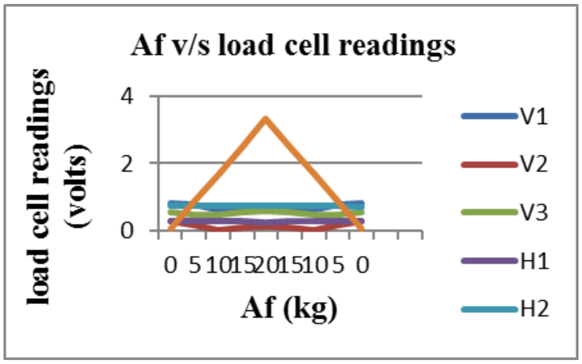

Figure 2. Af v/s load cell readings

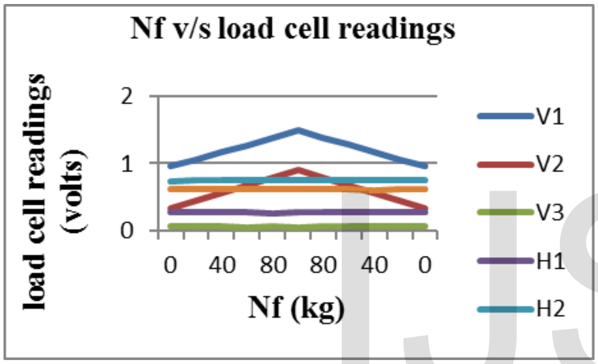

Figure 3. Nf v/s load cell readings

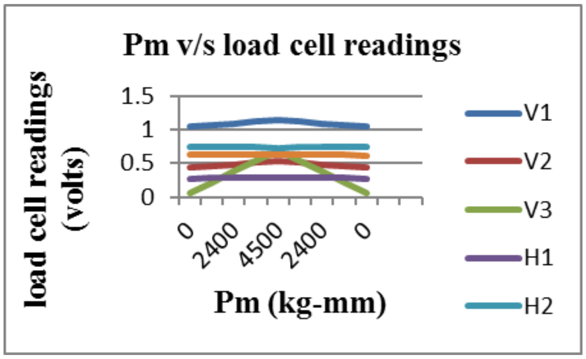

Figure 4. Pm v/s load cell readings

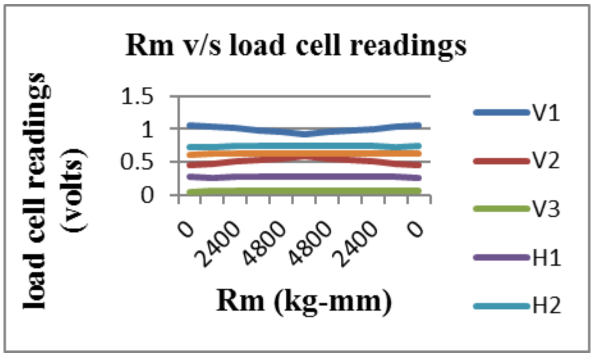

Figure 5. Rm v/s load cell readings

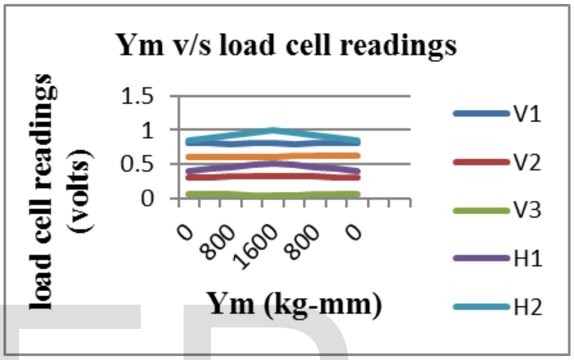

Figure 6. Ym v/s load cell readings

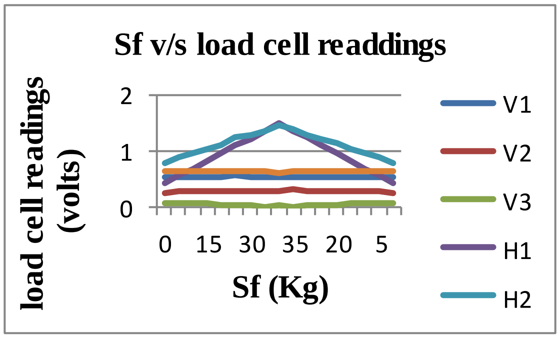

Figure 7. Sf v/s load cell readings

The calibration data shows that the balance behaves in a linear fashion in the range of loads applied. Percentage error is less than 1% of maximum load in each component.

5 THE CONCEPT OF I-BEAM AND SPRING ELEMENT

I-Beam

Fig. 8 (a)

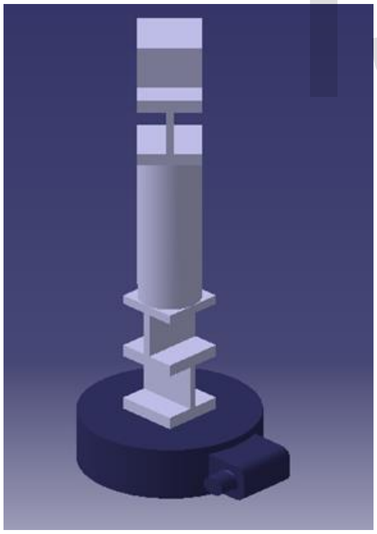

Fig.8 (b

Figure 8. Force measuring element without and with I-beam

5.1 FE Analysis of Force Measuring element without and with I-beam

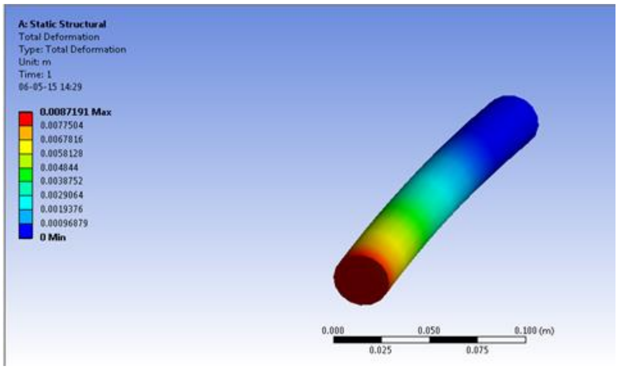

Fig.9 (a)

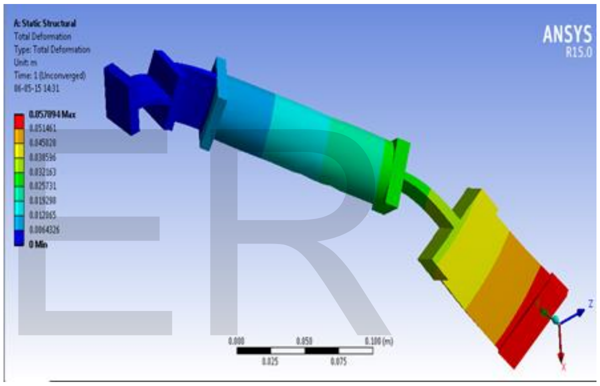

Fig.9 (b)

Figure 9. FE analysis of force measuring elements

A study was carried out on various configurations of force measuring elements using Finite Element Analysis. It was found that an I- beam induced in-between type of force measuring element met all requirements and was found to be sensitive only to the normal loading and insensitive to all other loads and moments. Static FE analysis of the force measuring element was carried out. An attempt was made to reduce the coupling between various forces & moments and to make the components sensitive only to their respective normal loads and to protect the load cells.

5.2 Spring Element in place of Load cell

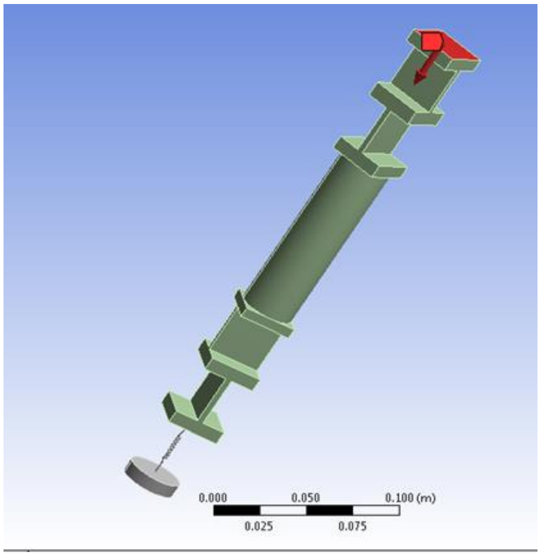

Figure 10. FE analysis of force measuring element by replacing sring inplace of load cell

The static FE analysis of the complete assembly force balance was carried out by replacing spring element in place of load cells, because there are no options to create and simulate load cells like elements in Ansys and some other available analysis software's. When a spring is compressed or stretched from its initial position after applying force on an element, the force or reaction it exerts is approximately proportional to its change in length.

6 FEM ANALYSIS OF EXTERNAL FORCE BALANCE

6.1 Normal Force, Rolling moment and pitching moment

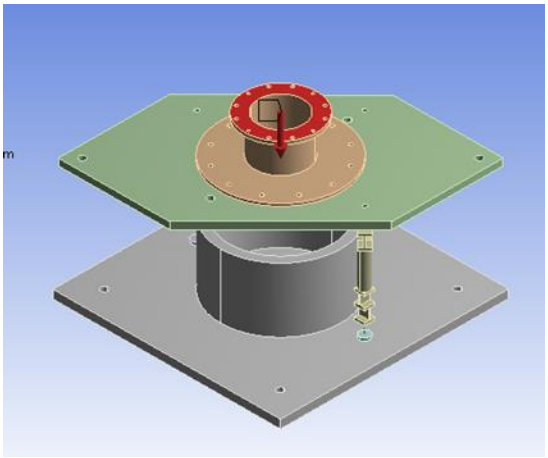

Figure 11. Nf, Rm, Pm measurement

The vertical components of the load on the model are sensed by the three load cells fitted vertically. These loads cells are designated as V1, V2 and V3.

Table 8. Nf measurement

Applied NF (N)	V1 (N)	V2 (N)	V3 (N)
-100	50.98	50.08	0.180
-200	100.29	100.26	0.554
-300	150.15	149.85	0.205
-400	200.20	200.15	0.340

6.2 Side Force and Yawing moment measurement

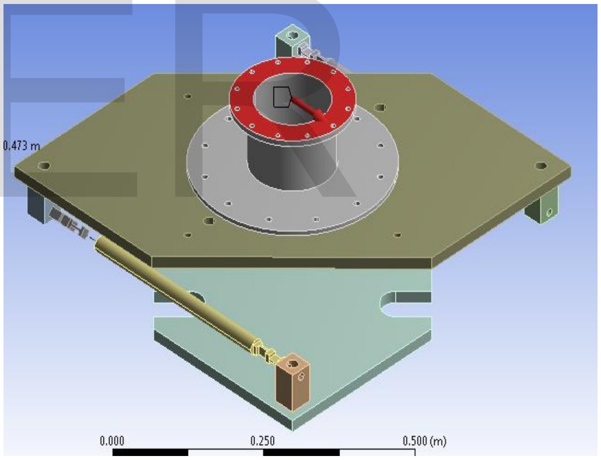

Figure 12. Sf, Ym Measurement

For sensing side force and yawing moment, there are two load cells fitted horizontally. These load cells are designated as H1, H2.

Table 9. Sf measurements

Applied SF (N)	H1 (N)	H2 (N)
50	-24.99	24.99
100	-49.99	49.99
150	-74.99	74.99
200	-99.99	99.99

6.3 Axial Force Measurement

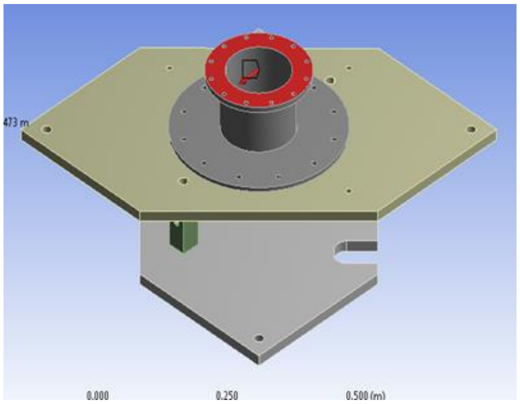

Figure 13. Af measurement

In the horizontal plane for sensing axial force one load cell is provided in axial direction and is designated as H3.

Table 10. Af measurement

Applied AF (N)	H3 (N)
25	24.99
50	49.99
75	74.99
100	99.99

6.4 Combined forces and Moments

Table 11. Combined forces

Applied load	(N)	V1 (N)	V2 (N)	V3(N)	H1(N)	H2(N)	H3(N)
Af	50	-0.00004	-0.0038	-0.0019	-0.0049	-0.00027	49.99
Sf	100	-0.00035	-0.00098	-0.00037	-49.99	49.99	-0.00022
Nf	200	-100.001	-100.001	0.544	-0.0002	-0.0009	-0.0003

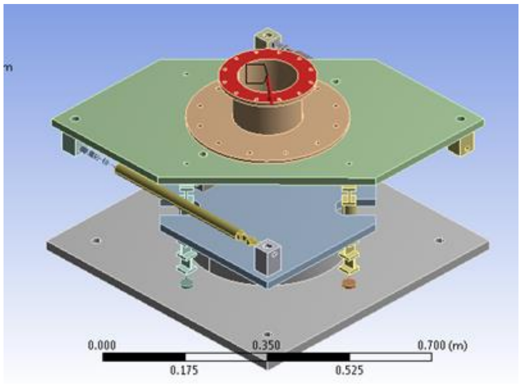

Figure 14. Combined forces

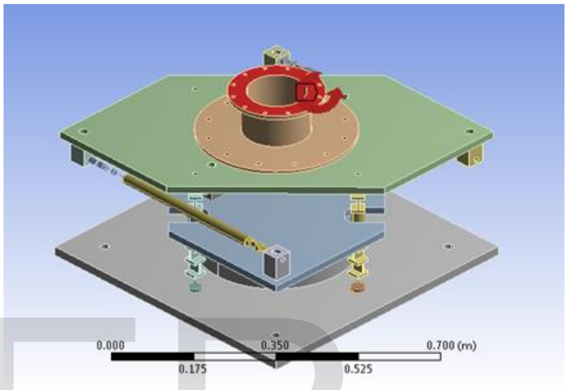

Figure 15. Combined moments

From V1, V2, V3, H1, H2 and H3 load cells the six-components of forces and moments are obtained.

6.5 Stress and deformation plot

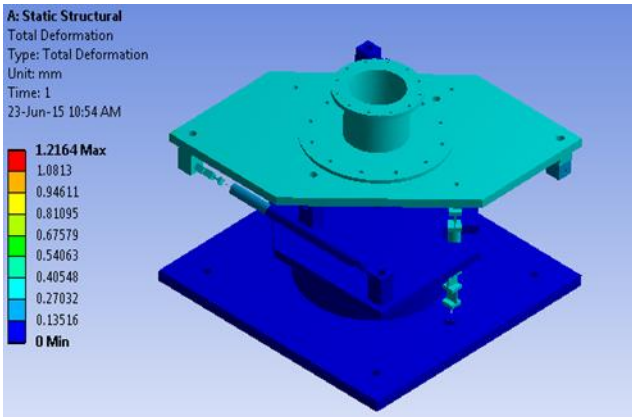

Figure 16. Deformation plot

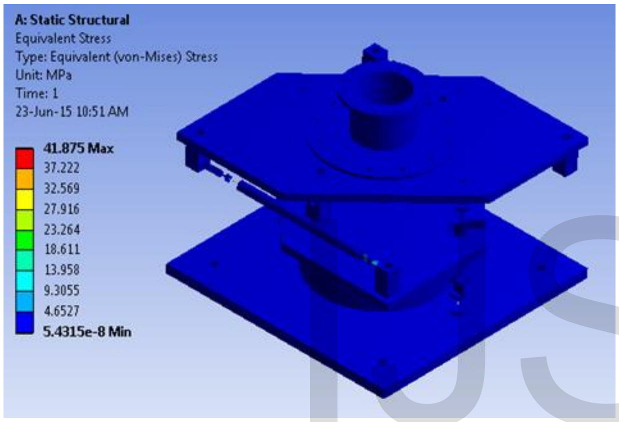

Figure 17. Stress plot

The static FE Analysis shows that, stresses and deformations in a designed external balance are within the limits for specified range of forces and moments (The material used EN24steel).

7 CONCLUSIONS

1. The calibration data shows that the balance behaves in a linear fashion in the range of loads applied. The transformation matrix obtained is almost a diagonal matrix as expected. Percentage error is less than 1% of maximum load in each component.

2. The balance can be utilised to determine aerodynamic loads within the specified range of forces and moments.

3. The FE Analysis shows that, stresses and deformations of the designed external balance are within the limits.

8 Acknowledgments

While bringing out this project to its final form, I came across several people whose contributions in various ways helped my field of research and they deserve special thanks. First and foremost, I would like to express my deep sense of gratitude and indebtedness to my supervisors Dr. S B Kandagal Principal Research Scientist, Dept. of Aerospace Engineering, IISc, Bangalore and Dr. J. Sharana Basavaraja Associate Professor BMS College of Engineering Bangalore. And for their invaluable encouragement, suggestions and support from an early stage of this research and providing me extraordinary experiences throughout the work. Above all, their priceless and meticulous supervision at each phase of work inspired me in innumerable ways I am highly grateful to Dr. D. Ghose, Chairman, Aerospace Engineering Dept. IISc Bangalore for giving me opportunity to carry out my thesis work at this reputed institute, which has given me exposure various methodologies of research. I also thank Mr. V Surendranath and Staff of OCWT, IISc, Bangalore for giving their valuable suggestion and time whenever asked for.

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