References

[1] J. Fraden, “Handbook of Modern Sensors: Physics, Designs, and Applications,” 3rd edition, Springer: New York, 2004, pp. 64-66,325-236.

[2] Y. Sun, B. J. Nelson, ” MEMS capacitive force sensors for cellular and flight biomechanics,” Biomedical materials, Mar 2007, pp.s16-s22

[3] S. Somlor, A. Schmitz, R.S. Hartanto, S.Sugano, “A prototype force sensing unit for a capacitive-type force-torque sensor,” System Integration, 2014, pp. 684-689.

[4] A. A. Barlian, W. T. Park, J. R. Mallon, A. J. Rastegar, and B. L. Pruitt, “Review: Semiconductor Piezoresistance for Microsystems,” Proceedings of the IEEE, Vol. 97, No. 3, Mar 2009, pp. 513-552.

[5] W. Hernandez, “Improve the response of a load cell by using optimal filtering,” Sensors 2006, Jul 2006, pp. 697-711.

[6] C. Lee , T. Itoh , T. Suga , “Micro machined piezoelectric force sensors based on PZT thin films,” IEEE Transactions on Ultrasonics, Ferroelectrics, and Frequency Control , Vol. 43, Issue 4 , Jul. 1996, pp. 553-559.

[7] J. G. Webster, “The measurement, instrumentation, and sensors handbook,” 1st edition, CRC Press, December 1998, pp. 23.3-23.7.

[8] R. Pacnik, F. Novak, “A high- sensitivity hydraulic load cell for small kitchen appliances,” Sensors 2010, Sep 2010, pp. 8452-8465.

[9] H. C. Smith, “The illustrated guide to aerodynamics,” 2nd edition, McGraw-Hill, Mar 1992, pp. 159-160.

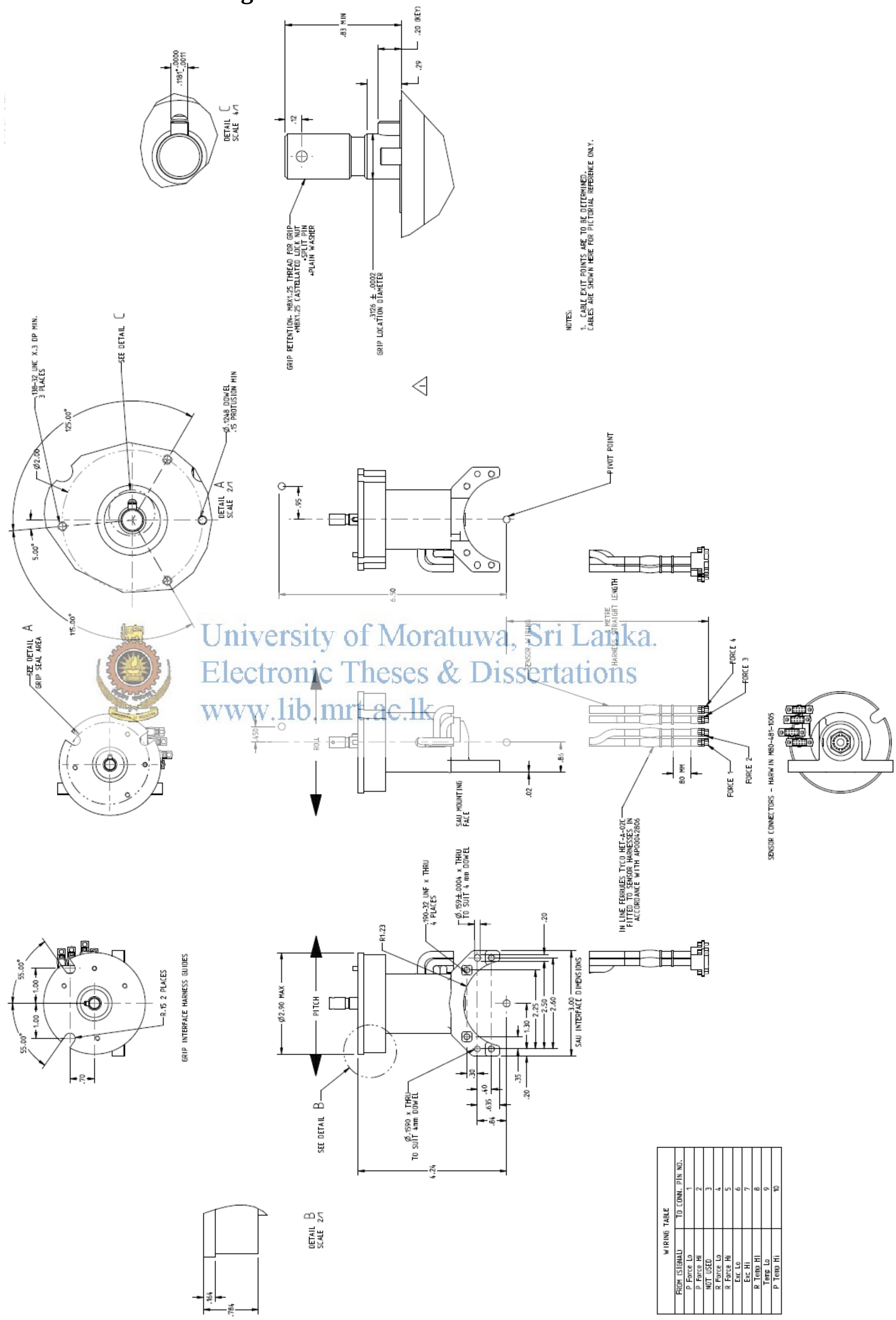
[10] I. Moir, and A. Seabridge, “Aircraft systems,” 3rd edition, John Wiley & Sons Inc, Jun 2008, pp. 04-10.

[11] R.W. Pratt, “Flight control systems practical issues in design and implementation,” Institution of Engineering and Technology, Mar 2000, pp. 06-19.

[12] F. P. Beer, E. R. Johnston, J. T. Dewalt, and D. F. Mazurek “Mechanics of Materials,” 5th ed. New York: McGraw-Hill, 2009, pp. 216–217.

[13] R. J. Wood, K-J Cho, and K. Hoffman, “Novel Multi Axis Force Sensor for Micro robotics Applications,” Smart Materials and Structures Journal, IOP Science Vol. 18 , Nov 2009, pp7.

Appendix A
Source control drawing of DAFSA



Appendix B
Mathematical model of Concept 5

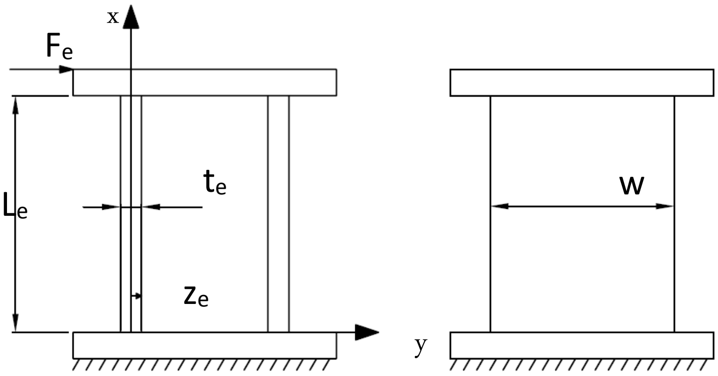


Figure B1. "Concept 5" design simplified sketch of the sensor element.

Stress and strain of the beam has following relation while stress remains well below the yield strength of the material [12]. Assuming material is homogeneous.

$$\sigma = \frac{Mz}{I} \qquad \text{(B1).}$$

$$\sigma = E\varepsilon \qquad \text{(B2).}$$

M is the bending moment, z is the distance from the neutral axis to a point of interest. E is the elastic modulus and I is the second moment of area. I must be calculated with respect to the centroidal axis perpendicular to the applied loading. σ is tensile stress and ε is strain of the beam.

Bending moment distribution along the beam of a clamped guided beam is describing as follows [13]. f is the force applied to the perpendicular to the centroidal axis and L is the length of the beam.

$$M = f\left(\frac{L}{2} - x\right) \qquad \text{(B3).}$$

$$M_{x_e} = f\left(\frac{L_e}{2} - x\right) \qquad \text{(B4).}$$

w and t are with and thickness of the beam respectively.

$$f = \frac{F_e}{2} \qquad \text{(B5).}$$

F_e is the force element of the total force which effect to the sensor element only.

$$z_e = \frac{t_e}{2} \tag{B6}$$

Considering equation (B1) and (B2)

$$\varepsilon = \frac{Mz}{EI} \tag{B7}$$

By substituting (B4), (B5) and (B6) in (B7)

$$\varepsilon_e = \frac{F_e t_e (L_e - 2x)}{8EI_{x_e}} \tag{B8}$$

I_{x_e} and I_{x_s} are second moment of area of the sensor element and the shaft respectively.

Using (B4) and (B5)

$$M_{x_e} = \frac{F_e}{2}\left(\frac{L_e}{2} - x\right) \tag{B9}$$

Deflection y at any given point of beam can be explaining using following equation [12].

$$\frac{\partial^2 y}{\partial x^2} = \frac{M_x}{EI} \tag{B10}$$

Calculating the displacement $y_{(x)_e}$ of the sensor element

$$\frac{\partial^2 y_{(x)_e}}{\partial x^2} = \frac{F_e (L_e - 2x)}{4EI_{x_e}} \tag{B11}$$

$$y_{(x)_e} = \frac{F_e}{4EI_{x_e}}\left(\frac{L_e x^2}{2} - \frac{x^3}{3}\right) \tag{B12}$$

Deflection of the extreme end ($x = L_e$) of the sensor element is.

$$y_{(L)_e} = \frac{F_e L_e^3}{24EI_{x_e}} \tag{B13}$$

Considering the shaft of the sensor assemble.

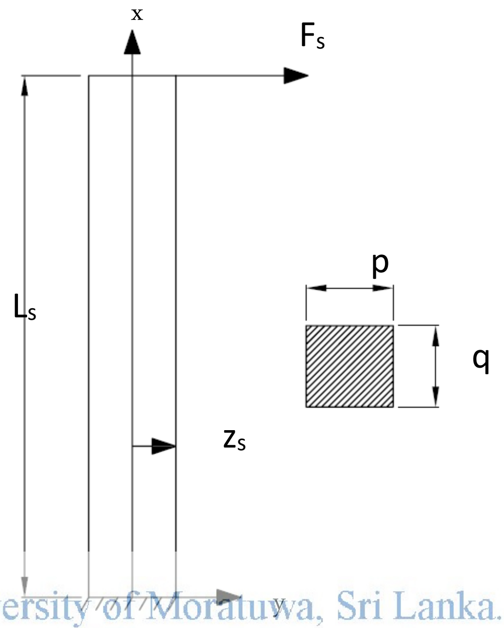


Figure B2. “Concept 5” design simplified sketch of the shaft.

Bending moment distribution along the beam of a cantilevered beam is describing as follows.

$$M = f(L - x) \qquad \text{(B14).}$$

$$M_{x_s} = F_s(L_s - x) \qquad \text{(B15).}$$

F_s is the force element of the total force which effect to the shaft only.

Substituting (B15) in (B10)

$$\frac{\partial^2 y_{(x)_s}}{\partial x^2} = \frac{F_s(L_s - x)}{EI_{x_s}} \qquad \text{(B16).}$$

To calculate the displacement $y_{(x)_s}$ of shaft

$$y_{(x)_s} = \frac{F_s}{EI_{x_s}}\left(\frac{L_s x^2}{2} - \frac{x^3}{6}\right) \qquad \text{(B17).}$$

Deflection of the extreme end $(x = L_s)$ of the shaft

$$y_{(L)_s} = \frac{F_s L_s^3}{3EI_{x_s}} \quad \text{(B18).}$$

At contacted point $L_s = L_e$ and contacted point displacement $y_{(L)_e}$ of the sensor element and displacement $y_{(L)_s}$ of the shaft should be same.

Using equations (B13) and (B18)

$$\frac{F_s}{I_{x_s}} = \frac{F_e}{8I_{x_e}} \quad \text{(B19).}$$

F is the total force acting on the pitch or roll direction.

$$F_s + F_e = F \quad \text{(B20).}$$

By substituting F_s from (B19) in (B20)

$$F_e = \frac{8FI_{x_e}}{I_{x_s} + 8I_{x_e}} \quad \text{(B21).}$$

By substituting F_e in (B8)

$$\varepsilon_e = \frac{Ft_e(L_e - 2x)}{E(I_{x_s} + 8I_{x_e})} \quad \text{(B22).}$$

$$I_{x_e} = \frac{wt^3}{12} \quad \text{(B23).}$$

$$I_{x_s} = \frac{qp^3}{12} \quad \text{(B24).}$$

$$\varepsilon_e = \frac{12Ft_e(L_e - 2x)}{E(qp^3 + 8wt^3)} \quad \text{(B25).}$$

q and p are with and thickness of the shaft respectively. Using the equation (B25) it is possible to select the p, q, w, t and L_e which give required strain at the total force.

`