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Design and Analysis of an Aircraft Wing Structure

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Abstract:
Structural design plays a major role in the design of any aircraft or spacecraft. The wing analysis is important in aircraft design as wings undergo various loads and stresses. The objective of present work is to determine wing structural loading for a conventional aircraft and perform its structural analysis. Schrenk's curve has been plotted and load distribution over the wingspan has been calculated and tabulated. Bending moment, shear force and torque calculations for the conventional aircraft wing has been performed at different wing stations and the detailed results are presented.

Keywords: *Aircraft wing, bending moment, shear force, torque, structural analysis*

I. INTRODUCTION

Design and analysis of aircraft/spacecraft structure is a very important as such structures should be highly reliable. The structural strength of an aircraft is dependent upon the maximum load factor that an aircraft can withstand at any velocity. This strength is usually characterized using a velocity-load factor diagram. Lift force, drag, and thrust create loading over aircraft structures. Aircraft structures are also subjected to loads due to gust, control surface movements, fatigue, bird strikes or lightning strikes, etc. So they are usually designed with a safety factor of 1.5. The aircraft wing analysis is one of the most important elements of the structural design and analysis of an aircraft. The wing is subjected to unsymmetrical loads acting on the spar made of 'I' section and stringers to carry bending loads and shear loads on the wings. The force and bending moment diagram of the wing must be made in the beginning of the analysis. The maximum bending stress produced in each member should be less than the yield stress of the material. Megson [1] discussed the procedure for solving of bending, torsion and shear problems of thin walled beams. Bruhn [2] discussed the basic knowledge on the preliminary design methods. Raymer [3] evaluated the various factors involved in aerodynamics and propulsion design. Other several researchers [4-6] interpreted the importance of flight envelope and determined different structural loads on an aircraft. Even various other design studies are existing focusing on several other factors in aircraft technology and principles [7-9]. The objective of present work is to calculate the structural responses of an aircraft wing from root to tip.

II. Mathematical Calculations

The numerical calculation for the wing analysis of a small aircraft (two seater) is discussed in this section. The load distribution is calculated after calculating the total load on the wing. It is assumed that every load acts on the span wise centre of each span section. The Schrenk's method is applied to find the load distribution of the wing. In this technique the plane from the wing is drawn with semi-span along the *X*-axis and the chord on the *Y*-axis. The formula for wing lift distribution is derived by Schrenk [10] and is altered to assume zero lift at the wing section within the fuselage. The formula gives the value of the lift for span unit. The quadrant of an ellipse which is equal to the area of the wing span is drawn. Semi major axis is taken as semi span. A curve is plotted joining the midpoints of the plan form and elliptical quadrant is drawn. This curve is known as Schrenk's curve. This gives the lift distribution. The Schrenk's curve is the mean of the wing plan form line and the elliptical curve which is also calculated and tabulated and the curves are drawn. The height of the Schrenk's at various points is measured. Load intensity is calculated from Eq. (1).

$$\text{Load intensity} = \frac{\left(\frac{W}{2}\right)\times Y_o}{A} \quad (1)$$

Where Y_o is the height of the Schrenk's curve at root (m) and A is the area under Schrenk's curve. Area under the curve is calculated and the Schrenk's curve height at root is determined using this area. These values are substituted in the load intensity to obtain the value at root. At other locations load intensity is calculated considering intensity at root (as in Eq. (2)). Schrenk's curve value at different locations with respect to root is also calculated.

$$\text{Load intensity at location } `n\text{'} = \text{Load intensity at root} \times (Y_n/Y_o) \quad (2)$$

The structural load is calculated assuming it varies with square of the chord. The load at any location is given by KC_x^2, where K is constant and C_x is the chord at location X. The wing is assumed to be tapered linearly from root to tip the expression is given by Eq. (3).

$$C_x = aX + b \quad (3)$$

Structural weight of the wing structure W_s at the sections is determined using the Eq. (4). W_s can be related with structural load intensity which is given as (KC_x^2) where K = 0.108 is a constant.

$$(W_s/2) = \int kC_x^2 dx\,(0, b/2) \quad (4)$$

The resultant load acting on the wing is the difference between the upward load intensity and the downward structural load intensity. The load intensity distribution is tabulated and plotted and the result load is given by the average between two points multiplied by distance between them. The resultant acts at the midpoint between them. The shear force at any section is obtained by the summation of the resultant loads. Bending moment at any point is determined by the moment of individual loads about that point. The force and bending moment diagrams are drawn from the calculated values. The torque is given by the product of the resultant force and the distance between the elastic axis and the centre of pressure. The elastic axis generally lies at 35 % of the mean aerodynamic chord (mac). The location of centre of pressure (cp) is calculated as in Eq. (5).

$$x_{cp}/c = (x_{ac}/c) - (c_{mac}/c_L) \quad (5)$$

III. RESULTS AND DISCUSSIONS

In the present analysis, the aircraft is considered to have a gross weight of 30000 N and payload 150 kg. It is designed to cruise at an altitude of 8500 m from sea level. The wing is assumed to be tapered linearly from root to tip. The aerodynamic loads will be distributed over the primary lifting surface, wing. Specifications considered in present wing design problem are: Wing span = 13.45 m, Semi span = 6.75 m, Root chord = 1.73 m, Tip chord = 0.869 m, Semi planform area = 10.49 m^2, Semi major axis, b = 2 m, Schrenk's curve height (root) Y_o = 2.591 m. The load distribution is calculated as discussed in previous section. Every load is assumed to act on the span wise centre of each wing station. The semi span is divided equally and numbered 1 to 10, each division of

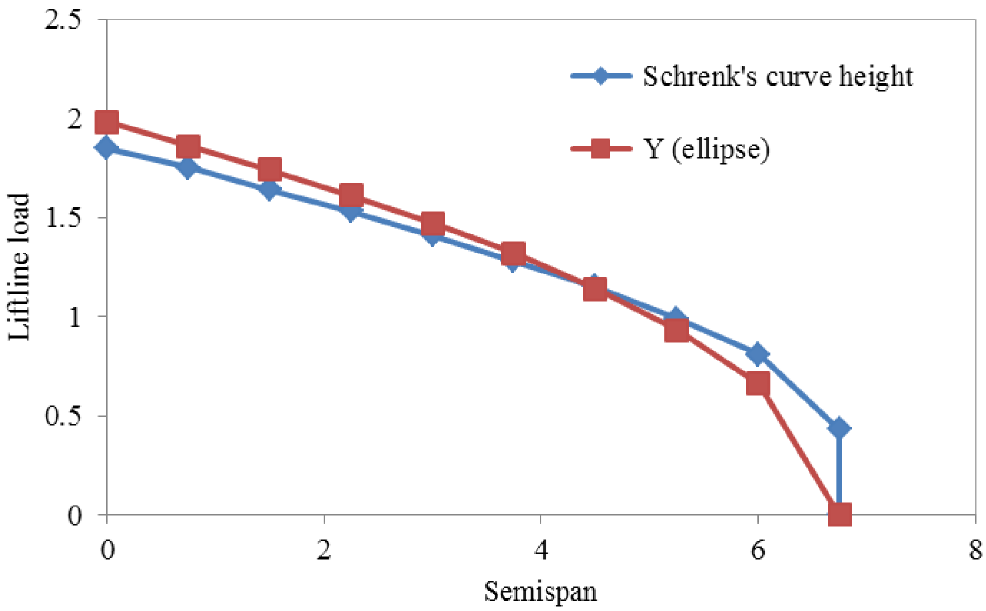
January - February 2020
ISSN: 0193 - 4120 Page No. 6952 - 6958

0.75 m. The lift contribution of the fuselage is assumed to be zero (this means that the load which would act in correspondence of the fuselage, is shifted externally to the wing) leading to more conservative results on the wing loads since they provide higher bending. Schrenk's curve height is calculated at different wing stations and results obtained are presented in Table 1. Then using Schrenk's curve height, the Schrenk's curve is plotted as in Fig. 1 for present aircraft loading case. From the Schrenk's curve, it is observed that the load distribution is low at the tip and it increases as we move along the span of the wing and becomes high at the root of the wing. The wing lift distribution and resultant load is presented in Table 2[1-13].

Table 1. Calculated height of Schrenk's curve at different wing stations.

Semi span (m)	*Y*(ellipse) (m)	Chord (m)	Schrenk's curve height (m)
0	1.98	1.73	1.85
0.75	1.86	1.64	1.75
1.50	1.74	1.54	1.64
2.25	1.61	1.45	1.53
3	1.47	1.35	1.41
3.75	1.32	1.25	1.28
4.50	1.14	1.16	1.15
5.25	0.93	1.06	0.99
6	0.66	0.97	0.81
6.75	0	0.86	0.43

Fig. 1. Schrenk's curve.



TEST Engineering & Management
January - February 2020
ISSN: 0193 - 4120 Page No. 6952 - 6958

Table 2. Resultant load calculation along the wingspan using Schrenk's curve.

Height from Schrenk's curve (m)	Area under the curve (m^2)	Load intensity (kN/m)	Structural weight (kN)	Lift (kN)	Resultant load (kN)
1.85	1.44	3.20	1.02	2.55	1.53
1.75	1.35	3.02	0.91	2.40	1.48
1.64	1.26	2.83	0.80	2.38	1.57
1.53	1.15	2.64	0.70	2.35	1.64
1.41	1.04	2.43	0.61	2.31	1.69
1.28	0.92	2.22	0.52	2.25	1.72
1.15	0.77	1.98	0.44	2.15	1.70
0.99	0.59	1.72	0.37	1.96	1.59
0.81	0.24	1.40	0.30	1.06	0.75

The bending moment at any point is calculated by determining the moment of the individual loads about that point. Using the calculated values, the bending moment and shear force at each wing station is tabulated. The bending moment and shear force values from root to tip is shown in Table 3. It is found that bending moment increases from tip to root and reaches the maximum value of 39.31 kNm at wing root. Maximum shear force of 13.71 kN is observed at wing root. Location of centre of pressure and mean aerodynamic chord in present analysis is calculated and presented in Table 4. The torque is given by the product of the resultant force and the distance between the elastic axis and the centre of pressure. As discussed earlier, the elastic axis generally lies at 35 % of the mean aerodynamic chord. The obtained numerical value of torque from wing tip to root is presented in Table 4. The bending moment diagram is plotted with bending moment in the *Y*-axis and semi span in the *X*-axis. Similarly the shear force diagram and torque diagram can be plotted using the obtained values. Thus the resultant distribution of shear force, bending moment, and torque along wing span is presented in Fig. 2. Thus the structural responses (bending, shear, and torsion) of an aircraft wing are obtained and presented in detail in this work [14-19].

Table 3. Shear force and bending moments at different wing stations.

Resultant load	Semi span	Shear force (kN)	Bending moment (kNm)
1.530	0	13.716	39.312
1.488	0.75	12.186	30.173
1.573	1.5	10.697	22.149
1.645	2.25	9.124	15.306
1.699	3	7.479	9.697
1.726	3.75	5.780	5.324
1.709	4.5	4.053	1.347
1.590	5.25	2.343	0.564
0.753	6	0.753	0

0	6.75	0	0

Table 4. Torque at different wing stations.

Semi span	Resultant load (kN)	Chord (m)	X_{cp}	MAC	Elastic axis	Torque (kN/m)
0	1.530	1.738	0.844	0.287	0.101	1.138
0.75	1.488	1.642	0.798	0.256	0.089	1.053
1.5	1.573	1.546	0.751	0.227	0.079	1.056
2.25	1.645	1.45	0.704	0.200	0.070	1.044
3	1.699	1.354	0.658	0.174	0.061	1.014
3.75	1.726	1.258	0.611	0.150	0.052	0.964
4.5	1.709	1.162	0.564	0.1285	0.045	0.888
5.25	1.590	1.066	0.518	0.108	0.037	0.763
6	0.753	0.970	0.471	0.089	0.031	0.331
6.75	0	0.874	0.424	0.072	0.025	0

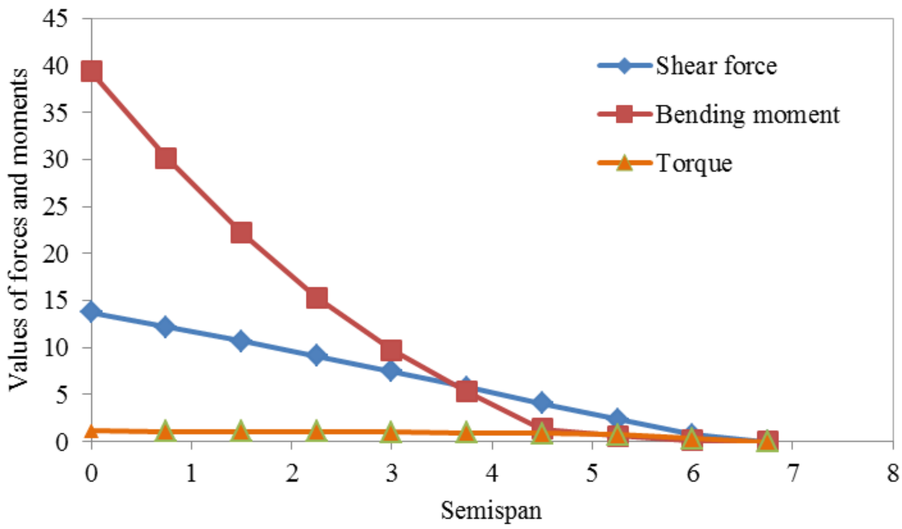


Fig. 2. The resultant distribution of shear force, bending moment, and torque along wing span.

IV. CONCLUSION

The present work discussed the structural design and analysis of an aircraft wing in a simple manner. Wing is the primary lifting surface and large amount of aerodynamic load acts over it. The wing is equally divided and numbered from 1 to 10. Resultant load distribution in wing stations is calculated applying Schrenk's curve approach. Then the bending moment, shear force and torque at different wing stations are calculated. One

January - February 2020
ISSN: 0193 - 4120 Page No. 6952 - 6958

advantage of present work is that this work considered wing of a 2 seater aircraft and the calculation of structural response is described step by step. These calculations can be implemented on any aircraft wing. This work can be extended by carrying out the analysis of internal members of wing like spars, longerons, and ribs.

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