Estimating Sailplane Mass Properties

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Abstract

Estimates of the sailplane inertia parameters (mass, centroid and moment of inertia) are often needed for flight mechanics analysis. This paper discusses a moment of inertia estimation method for sailplanes using representative geometric figures. Results are compared with published moment of inertia values. The accuracy and utility of the method is discussed. A prismoid wing model was found to be a reasonable geometric representation of the sailplane wing. Additionally, the requirement for added mass correction to the moment of inertia is considered. Although it is acknowledged that added mass effects are subtle and simple theoretical estimation methods should be avoided, one estimation method that only requires the principal sailplane dimensions is presented. Finally, the effect on mass moment-of-inertia when increasing the wingspan is investigated.

Nomenclature

b	wing span
c	mean aerodynamic chord
CAD	computer aided design
CFD	computational fluid dynamics
CG	centre of gravity
d	width of ellipsoid
D_λ	correction factor for taper ratio
D_Γ	correction factor for dihedral
I	inertia tensor
$\overline{I}$	moment of inertia about the centrodial axis
I_{xx}	moment of inertia about the X-axis
I_{yy}	moment of inertia about the Y-axis
I_{zz}	moment of inertia about the Z-axis
k	coefficient of added mass
K	volume of added mass
L_f	sailplane fuselage length
m	mass
MAC	mean aerodynamic chord
MoI	moment of inertia
PoI	product of inertia
T	kinetic energy
U	velocity
w	depth of ellipsoid
x	position of component centroid relative to the reference X-axis
x_{cg}	position of CG relative to the reference X-axis
y	position of component centroid relative to the reference Y-axis
y_{cg}	position of CG relative to the reference Y-axis
z	position of component centroid relative to the reference Z-axis
z_{cg}	position of CG relative to the reference Z-axis
ρ	local air density

Subscripts

a	apparent moment of inertia
cg	centre of gravity
f	fuselage
i	component number

Introduction

Sailplane mass properties are important for flight mechanics analysis and flight simulation. Unfortunately, for existing sailplanes, mass properties such as the MoI are rarely published and, when designing a new sailplane, they are obviously not initially available. Mass MoI estimation can be critical and has been highlighted earlier, in a research project where the aim was to predict aerodynamic and dynamic behavior of the ASW-24 sailplane.[1]

Historically the approach to this matter has been by experimental determination using pendulum methods on full scale aircraft.[2] However, this requires access to the full scale aircraft and appropriate equipment. This paper will discuss the use of a theoretical method that can be used to estimate mass properties for sailplanes by using design data only. To compare the estimations with published data, concerning sailplane types ranging over some 40 years, data are derived necessarily from sources ranging over this period.

Mass MoI is estimated for four sailplanes: Laister-Kaufmann LK-10A, Schweizer SGS 1-36, Schempp-Hirth Standard Cirrus and the Schempp-Hirth Nimbus 2A. The LK-10A and the SGS 1-36 were chosen due to the availability of published experimentally determined MoI values. The LK-10A was used in a research project involving flight measurements at Mississippi State University,[3] and the SGS 1-36 has been used for similar purposes at NASA[4]. For research purposes, these two particular sailplanes were modified and each had an on-board instrumentation package installed. The SGS 1-36 used by NASA is shown in Fig. 1. The Standard Cirrus and Nimbus 2A were chosen as they appear to have been used as "Sailplane 3" and "Sailplane 5" respectively in an extensive qualitative evaluation of the handling of a range of contemporary sailplanes.[5]

Additionally, the significance of added mass effects is discussed. The added mass is the correction to the solid body mass due to the surrounding air. To consider added mass effects or not, involves a question of relative effects. As the mass of the surrounding air approaches a significant fraction of the mass of the wing, the added mass effect will have a significant impact on flight characteristics. With the advancement of light sailplanes and solar powered flight, both having low wing loading, added mass effects have become increasingly important.

Finally, after having, the authors believe, established a trustworthy estimation method, this paper will investigate the effect upon MoI of increasing the sailplane's wingspan. Modern sailplanes continue to employ increased wingspan in pursuit of superior gliding performance; it is, therefore, worthwhile considering scaling effects upon MoI when increasing wingspan in a design.

Representative geometric figures method

In addition to the sailplane CG, the inertia tensor *I* is of particular interest in flight mechanics. For a rigid body with symmetry relative to the XZ-plane body axes we have

$$I = \begin{pmatrix} I_{xx} & 0 & -I_{xz} \\ 0 & I_{yy} & 0 \\ -I_{xz} & 0 & I_{zz} \end{pmatrix} \qquad (1)$$

where I_{xx} ,I_{yy} and I_{zz} are the principal MoI and I_{xz} is the PoI. To estimate MoI and PoI we have used the representative geometric figures method. In this method aircraft components are replaced by geometric figures where the section properties are available, e.g. formulae for MoI and centroid (Fig. 2).

NASA published an implementation of this method for estimating mass properties of light single engine aircraft.[6] The method can be implemented for a sailplane by using the following steps:

1) Principal sailplane components are represented by geometric figures as in Table 1.
2) A reference axis system for measuring relative positions is established.
3) The CG of each component is assumed to be at the centroid. The relative position of the component centroid is measured from a scale drawing.
4) Component masses are estimated. Advice on component mass breakdown may be found in the sailplane documentation, e.g. the Flight Manual.
5) The estimated 3-dimension CG position of the sailplane can now be calculated.
6) Component height, length, width or radius are determined as appropriate.
7) MoI about the body axis is estimated using the appropriate equations for the MoI of the representative geometric figures which can be found in a design handbook or guide, e.g. as published by AIAA.[7]

The parallel-axis theorem is used to transfer the MoI about the centroidal axis to the aircraft body axis. For the complete aircraft, represented by components i = 1,…, n. for the X-, Y- and Z-body axis:

$$I_{xx} = \sum_{i=1}^{n} \bar{I}_i + m_i((y_i - y_{cg})^2 + (z_i - z_{cg})^2) \qquad (2)$$

$$I_{yy} = \sum_{i=1}^{n} \bar{I}_i + m_i((x_i - x_{cg})^2 + (z_i - z_{cg})^2) \qquad (3)$$

$$I_{zz} = \sum_{i=1}^{n} \bar{I}_i + m_i((x_i - x_{cg})^2 + (y_i - y_{cg})^2) \qquad (4)$$

$$I_{xz} = \sum_{i=1}^{n} m_i(x_i - x_{cg})(z_i - z_{cg}) \qquad (5)$$

where $\bar{I}_i$ is the component MoI about the centroidal axis, m_i is component mass and (x_{cg}, y_{cg}, z_{cg}) is the position of the estimated CG.

Component mass breakdown when using the representative geometric figures method

The accuracy of the representative geometric figures method depends on the reverse engineering process of component mass breakdown. Mass data for contemporary sailplanes was obtained and used to estimate component masses (Appendix). It can be observed that the total wing mass is approximately half the sailplane's empty mass. The exception being the 20.3m span Nimbus 2A where the wing mass is 64% of empty mass. The sample of sailplanes in the Appendix is varied in the sense of time frame of design and construction methods. Therefore, the relationship between total wing mass and empty mass should (ideally) take account of analogous values obtainable from a range of comparable aircraft.

The wing of a sailplane, representing such a large part of the sailplane structure, needs to be modelled accurately. From studying cutaway drawings of sailplane wings, it is assumed that a prismoid is a reasonable geometric representation. To compare the mass distribution of the prismoid with a sailplane wing, a CAD program was used to generate a prismoid wing model based on measured wing dimensions and masses for the AS-K 13, AS-K 18 (Fig. 3), Standard Cirrus and Nimbus 2A. Masses were measured using a 2-point weighing procedure involving standard calibrated aircraft weighing balances. A comparison of the prismoid wing model and the measured wing CG position is shown in Table 2. The prismoid wing CG position is within 5% of the measured position. This indicates that the prismoid wing model is a reasonable representation of the sailplane wing.

Comparison with published data

Using the method described above, MoI values were estimated for the Laister-Kaufmann LK-10A and the Schweizer SGS 1-36. Published values for PoI were unfortunately not available and that aspect has not been considered in this comparison. A comparison of estimations with published data is presented in Table 3. Published values are from Refs. 3 and 4.

For the SGS 1-36, with maximum difference of 11%, correlation with the published data is acceptable. However, for the LK-10A with 45% difference for MoI about the roll axis, correlation appears to be poor. As a cross-check, firstly, we can apply the perpendicular axis theorem:

$$I_{xx} + I_{yy} \approx I_{zz} \tag{6}$$

In three of the four cases (the published value for the 1-36 and the modeling cases for both it and the LK-10), relation (6) seems to fit within 5%. However, in the case of the LK-10A, the published values for I_{xx} (= 784 kg·m²) and I_{yy} (= 590 kg·m²), sum to 1374 kg·m². Compared with the published value of 2,018 kg·m², this shows 32% net or 48% gross difference.

Secondly, the published I_{xx} value for the LK-10A is only a little greater than half that of the geometric figures model and of the SGS 1-36 published. For these two sailplanes, having approximately the same mass and configuration, such a variation in MoI seems unlikely.

There are four main sources of error in the representative geometric figures method:

1) The geometric figure does not represent fully the aircraft component.
2) Dimensional measurement error.
3) Component CG not at the apparent centroid.
4) Incorrect component mass estimation.

For 1) – 3), it has been found to be essential that enough components are used so that errors in them tend to cancel each other out. However, the accuracy of this method depends upon the reverse engineering process of component mass breakdown, particularly for components with long moment arms. It is obvious that for the sailplane, the estimation result will be sensitive to the wing CG position. When an actual weight and balance report is available, similar CG positions would provide a good indication of a reasonable mass component breakdown.

An additional consideration: Added apparent mass effects

Consider a body moving through the air at a given velocity. To be able to derive the kinetic energy and the force necessary to accelerate the body in the ambient air, additional "apparent mass" should be added to the actual mass as shown by Munk.[8] This effect of motion of the ambient air will give rise to additional moment of inertia. Thus, the moment of inertia must be corrected for added mass due to the effect of the surrounding air. In particular, aircraft with low wing loading may require a substantial correction to MoI for such added mass effects. For the human-powered aircraft, Gossamer Condor and Albatross, flight tests showed that added mass effects greatly affected flight characteristics as indicated by the authors' statement:[9]

"Extremely light wing loading leads to a dominance of air apparent-mass effects on the effective heaving, rolling and pitching inertias. These effects make the Gossamers very difficult to control in roll, and extremely sensitive to wind gust disturbances."

They estimated added mass for the Condor (Fig. 4) by representing the lifting surfaces with conical air mass cylinders.[9] In principle this is the same technique as used in the representative geometric figures method employed for the present modeling. After accounting for added mass, the MoI about the X-axis was five times greater than the uncorrected value. However, research into the effect of added mass on parafoils, indicates that the effects are subtler.[10] Using a CFD tool to investigate the added mass for a flat wing, it was found that the numerical solution was sensitive to wing tip shape. Furthermore, when considering the spanwise camber of the parafoil, it was concluded that the roll inertia of a cambered wing about the roll center may be as small as 0.1 of the corresponding value for a flat wing.

Apparently, simple theoretical estimations of the added mass should thus be avoided and it is probably best to estimate added mass numerically using CFD software. Again, as for the solid mass MoI estimation, it is the sailplane wing that is of particular interest. Therefore, detailed three dimensional wing geometry data should be available for grid generation. If detailed wing geometry data is not available, or access to CFD software is limited, there is another estimation method that can be used for preliminary design studies. This theoretical estimation method (as outlined below) only requires the principal sailplane dimensions, such as can be found in a 3-view drawing.

The volume of added mass, K, is obtained by dividing the kinetic energy of the flow by the dynamic pressure occurring due to the body velocity.[8] Let U be the velocity and ρ the local air density, then

$$K = \frac{2T}{\rho U^2} \tag{7}$$

A non-dimensional quantity, depending only on the shape of the body and the direction of motion, is derived from this volume of added mass. This quantity is called the "inertia factor," or the "coefficient of additional apparent mass," and denoted as k.[8] The inertia factor, k, is, therefore, the apparent increase in mass of a body divided by the mass of air displaced by that body. A challenge in added mass estimation work is to find representative inertia factors for the body in question.

To estimate apparent MoI for the sailplane, the lifting surfaces are represented by flat plates and the fuselage by an ellipsoid. NACA has published equations for additional apparent mass and MoI for flat plates where the inertia factors are functions of the aspect ratio and were determined experimentally.[11] The subscript a denotes apparent MoI. For the lifting surfaces:

$$\begin{aligned} I_{axx} &= \pi\rho c^2 (\frac{1}{48} D_\lambda D_\Gamma k_{ax} b^3 \\ &+ \frac{1}{4} kb((y - y_{cg})^2 + (z - z_{cg})^2)) \end{aligned} \tag{8}$$

$$\begin{aligned} I_{ayy} &= \pi\rho c^2 (\frac{1}{48} D_\lambda D_\Gamma k_{ay} cb^2 \\ &+ \frac{1}{4} kb((x - x_{cg})^2 + (z - z_{cg})^2)) \end{aligned} \tag{9}$$

where b is span, c is the mean aerodynamic chord, k is the inertia factor, D_λ and D_Γ are the correction factors for taper ratio and dihedral respectively and k_a is the coefficient of apparent MoI. The apparent MoI for the flat plates about the Z-axis will be small and is disregarded.

Furthermore, the apparent MoI of the fuselage can be estimated using the theory of an ellipsoid in a three dimensional potential flow.[11] The subscript f denotes the sailplane fuselage.

$$\begin{aligned} I_{ayy} &= \frac{\rho}{5} k_{fay} L_f wd(\frac{L_f}{4} + \frac{3d^2}{2\pi}) \\ &+ \rho(k_{fz} L_f wd((x - x_{cg})^2 + (z - z_{cg})^2)) \end{aligned} \tag{10}$$

$$\begin{aligned} I_{azz} &= \frac{\rho}{5} k_{faz} L_f wd(\frac{L_f}{4} + \frac{3w^2}{2\pi}) \\ &+ \rho(k_{fy} L_f wd((x - x_{cg})^2 + (y - y_{cg})^2)) \end{aligned} \tag{11}$$

where L_f is fuselage length, w and d are average depth and width of the ellipsoid respectively. The apparent MoI for the fuselage about the X-axis is very small relative to that for the wing, so is disregarded.

The apparent MoI has been estimated for the Schweizer SGS 1-36 sailplane using Eqs. (8) – (11), with inertia and correction factors from NACA,[11] and the results presented in Table 4. As expected, it is the apparent MoI about the X-axis that has the largest value and represents an 11% correction to the mass MoI.

The effect on MoI of increasing wingspan

In modern sailplanes, increased wingspan is sought in the quest for improved gliding performance. To be able to investigate the effect this trend has on sailplane flight mechanics the methods described above are used to estimate mass and apparent MoI about the roll axis when increasing wingspan. As a start-point scaling datum, MoI is comprised of units of mass and radius-squared and mass scales as the cube of span. It follows that changes of scale result in 5th power scaling of MoI, i.e. a doubling or halving of scale will obtain MoI scaling by 32; even a modest scaling up of 10% will obtain ~65% increase in MoI. This might be termed the "naïve plank" model. This is an area amenable to further study using the 15m/18m class of sailplane where change of configuration is a matter of changing the outer wing panels.

Coupled with the prismoid wing model, a CAD program was used to model an increase of wingspan of the SGS 1-36 whilst the other dimensions and the taper ratio were kept constant. From Fig. 5 it can be seen that the effect of increasing the sailplane wingspan by 50% is to double the mass MoI about the roll axis.

Furthermore, mass MoI values were estimated for the two Schempp-Hirth sailplanes: the 15m span Standard Cirrus and the 20.3m span Nimbus 2A. For the Nimbus 2A, in addition to having a longer span than the Standard Cirrus, a higher density had to be used in the prismoid wing model to match the measured mass for the wing. This naturally increases the mass MoI even more. The results are shown in Table 5.

For apparent MoI estimation, if Eq. (8) is used for an increase in wingspan by 50% this will result in an approximately 250% increase in I_{ax}. However, it is unclear how well Eq. (8) and the inertia and correction factors determined experimentally by NACA will scale. To investigate the effect of added mass with increasing wingspan, future research should use CFD software to study the effects.

Discussion and Conclusions

The "representative geometric figures" method has been used in this work to estimate the mass properties of two sailplanes. This method is flexible in its implementation and readily amenable to configuration change (e.g. additional equipment or water ballast). For accuracy detailed mass breakdown is required. The prismoid wing model was found to be a reasonable geometric representation of the sailplane wing. Correlation with published mass MoI values was in the range 0-14 % with the single exception of the LK-10A published value for mass MoI about the roll axis. However, it is reasoned that this published value may not be accurate.

Added apparent mass correction to the MoI should be considered, in particular for aircraft of low wing loading. Prior research indicated that the added mass effects are subtle and simple theoretical estimation methods should be avoided. However, if detailed wing geometry data is not available, there exists an estimation method which only requires the principal sailplane dimensions. Apparent MoI was estimated for the SGS 1-36 using equations for apparent mass and MoI, and inertia and correction factors experimentally determined by NACA. The correction to the solid mass MoI about the roll axis was 11%. Presently, data is not available to check the accuracy of the apparent MoI estimation. Future research should endeavor to improve estimates for such corrections due to added mass, and thereby advance the knowledge of the apparent mass effect on aircraft flight mechanics.

The effect on mass MoI when increasing the wingspan of the SGS 1-36 prismoid wing model was investigated. The mass MoI about the roll axis doubles with a 50% increase in wingspan. If the density of the wing increases as a result of the increased wingspan, the mass MoI will increase even more. For the apparent MoI the increase is most likely of a much higher order. This underlines the importance of considering both mass and apparent MoI for sailplanes with low wing loading.

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Table 1

The sailplane components and the representative geometric figures

Sailplane component(s)	Geometric figure
Cockpit/Cabin area	Hollow box
Fixed equipment	Rectangular solid
Nose and tail cone	Hollow cone
Landing gear wheel	Solid cylinder
Vertical and horizontal tail surfaces	Rectangular sheet
Wing	Prismoid

Table 2

Comparison of the prismoid wing model CG and measured CG

Sailplane	Prismoid CG (m)	% of wing length	Measured CG (m)	% of wing length
AS-K 13	2.6	34	2.2	29
AS-K 18	2.4	31	2.7	35
Std. Cirrus	2.5	34	2.6	36
Nimbus 2A	3.3	34	3.5	35

Table 3
Comparison of the estimated mass MoI and published values

LK-10A[3]	Published values	Representative geometric figures method	% diff.
I_{xx} (kg·m²)	784	1,136	45
I_{yy} (kg·m²)	590	672	14
I_{zz} (kg·m²)	2,018	1,737	-14
CG (%MAC)	n/a	31	n/a
Mass (kg)	397	387	-3
SGS 1-36[4]			
I_{xx} (kg·m²)	1,375	1,271	-8
I_{yy} (kg·m²)	869	788	-9
I_{zz} (kg·m²)	2,214	1,962	-11
CG (%MAC)	33	29.5	-11
Mass (kg)	396	396	0

Table 4
Schweizer SGS 1-36 apparent moment of inertia estimation

	Estimated apparent MoI (kg·m²)
I_{axx}	156
I_{ayy}	15
I_{azz}	15

Table 5
Estimated mass MoI for the Std. Cirrus and Nimbus 2A

	Std. Cirrus	Nimbus 2A
I_{xx} (kg·m²)	1,262	4,501
I_{yy} (kg·m²)	416	692
I_{zz} (kg·m²)	1,621	5,102
CG (%MAC)	29.8	30.0
Mass (kg)	335	451

Figure 1 Schweizer SGS 1-36 (courtesy of NASA)

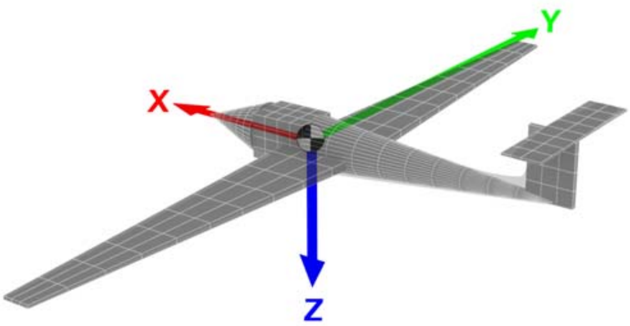

Figure 2 Concept drawing showing the representation of sailplane components by geometric figures.

Figure 3 CAD generated prismoid model of the Schleicher AS-K 18 wing.

Figure 4 The Gossamer Condor (courtesy of NASA).

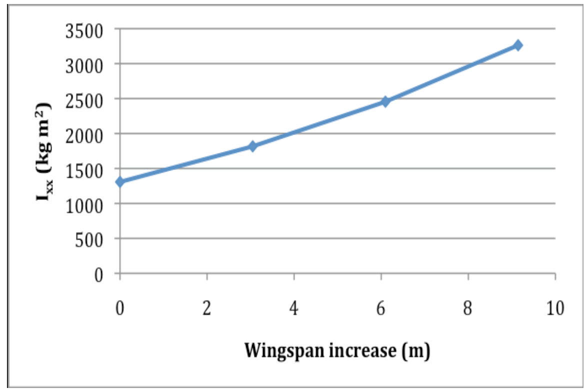

Figure 5 SGS 1-36 Estimated mass MoI variation with wing-span.

Appendix

Sailplane	First flight	Empty mass (kg)	Wing mass (kg)	Wing mass in % empty mass	Wing span (m)	Fuselage mass (kg)	Horiz. tail mass (kg)
Laister-Kaufmann LK-10A [[13] pp232-3, [15] p75]	1942	215.5	100	46	15.2	91.0	12
Bergfalke II/55 [[12] pp76-80, [a]]	1951	288.9	157.7	54	16.5	121.7	9.6
Lehrmeister FES 530 [[12] pp99-101, [a]]	1956	357.4	172.5	48	17.0	160.4	15.5
Schleicher AS-K 13 [[14] p98, [15] p122]	1966	289.8	156.9	54	16.0	123.8	9.1
Schempp-Hirth Std. Cirrus	1969	246.5	116.5	47	15.0	123.0	7.0
Schempp-Hirth Nimbus 2A	1971	364.1	233.6	64	20.3	123.5	7.0
Pilatus B-4 [[14] p145, [15] p88, [a]]	1972	245.8	137.3	55	15.0	98.2	10.8
Schleicher AS-K 18 [[14] p103]	1974	228.6	122.0	53	16.0	104.0	8.2
Schweizer SGS 1-36 [[14] p141, [b]]	1979	215.5	111.1	52	14.0	88.45	8.4

Note: Data concerning the masses of gliders were obtained from multiple sources (indicated by the references[12-15]). These were augmented by weighings' data for the Bergfalke II/55, Lehrmeister FS530 and Pilatus B-4 from the Norwegian Historical Sailplane Society.[a] Similarly, further data for the Schleicher AS-K13 and AS-K18 were obtained from weighings carried out at the RAF Chilterns Gliding Centre. Data for the Schempp-Hirth Std. Cirrus and Nimbus 2A were obtained from weighings at Bicester and Upavon, UK, respectively. The Schweizer 1-36 data were kindly provided by Mr. Les Schweizer[b] and are understood to derive from weighings by the manufacturer, Schweizer Aircraft Corp., Elmira, NY.

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