Modern Use of Spreadsheet Methods for Aircraft Design, Sizing, and Performance Analysis

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ABSTRACT

Spreadsheet programs, typified today by those running on Microsoft Excel™, have become endemic in the engineering community. This paper reports the experiences of this author, who has spent years developing a sophisticated non-spreadsheet program for aircraft design, sizing, and performance analysis, in developing a simplified spreadsheet method for similar tasks.

NOMENCLATURE

A = Aspect Ratio (span^2/reference area, applied to wings and tails)
L/D = Lift-to-Drag Ratio
RDS = Aircraft design software package (*"Raymer's Design System"*)
W_e = Aircraft Empty Weight
W_o = Aircraft Takeoff Gross Weight

INTRODUCTION

Beginning with VisiCalc™, the original "killer application" of early personal computer legend, the spreadsheet has been one of the main uses of PC's for both business and engineering analysis. While spreadsheet programs can attain impressive levels of complexity, they are most often used for more simplified analysis in which early "what-if" trade studies can be quickly assessed. Furthermore, they are especially useful for operation by non-expert, non-regular users due to their standardized appearance and input operation.

Over the past 20 years, aircraft designers such as Lockheed's Tony Hays[1] have created various spreadsheet programs to perform design tasks including mission sizing, performance analysis, and preliminary estimation of aerodynamics, weights, and propulsion.

This author has spent many years in the development of the RDS aircraft design software, a "hard-coded" program of 20,000+ lines of code that performs a full range of aircraft conceptual design tasks[2]. RDS has great capabilities and a user-friendly interface, but incorporates methods of sufficient fidelity and flexibility that they are best used by an engineer trained (or a student training) in aircraft conceptual design engineering methods.

Several years ago this author began writing a simplified aircraft design book[3] aimed at the homebuilding community. These are typically intelligent people with a great interest and love for airplanes, but most are not trained aeronautical engineers nor enthusiastic "computer geeks."

In writing the new book a primary goal was the presentation of a complete and self-contained method of design analysis, which could be completed using only a pocket calculator. In addition, it was decided to implement these simplified methods in a spreadsheet program that would be made available along with the book. This was done for two reasons – to make it easier for readers to do the analysis, and to make it easier for the author to do the examples in the book.

APPROACH

The approach, obviously, was to implement simplified aircraft analysis methods on a spreadsheet. Microsoft Excel™ 97 was used, with no use of Visual Basic or other analysis

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enhancements. A simple color scheme was used to identify required input fields and resulting answers. Comment fields were added to assist users.

The technical methods employed, as described in the book for homebuilders, are largely simplifications of the standard analysis methods described in this author's textbook *Aircraft Design: A Conceptual Approach*[4]. Aircraft are limited to subsonic piston-prop designs, which permits further simplifications in the methods.

Parasitic drag is estimated by the use of an "equivalent skin friction coefficient" or C_{fe}, selected from historical values. This is multiplied by wetted area, then divided by wing reference area as follows:

Parasitic Drag Coefficient: $$C_{D0} = C_{fe}\frac{S_{wet}}{S_{ref}}$$

Additional drag such as that due to fixed landing gear is added from historical values.

The drag-due-to-lift is found from the time-honored Oswald span efficiency factor ("*e*"), as follows:

Drag-due-to-lift-factor: $$K = \frac{1}{\pi A e}$$

Maximum lift is assumed to be 90% of the airfoil maximum lift, adjusted by the cosine of the wing sweep angle. Flap effects are treated by adding a historically based lift increment, adjusted by the flapped area.

Propulsion calculations are limited to piston-propeller aircraft. The user inputs specific fuel consumption and a propeller efficiency (η_P - found from tables provided in the book). Thrust is calculated using the standard equation derived from the definition of efficiency, or:

Thrust Produced: $$T = \frac{550\,bhp\,\eta_P}{V}$$

V = velocity (ft/sec)
bhp = engine brake horsepower

For pre-layout sizing calculations, the empty weight is determined by entering the coefficients of an empty weight ratio exponential equation based on historical regression analysis. For subsequent analysis of the baseline design layout, a standard weights sheet format including moment calculation is included. However, the actual component weights must be estimated "off line" using methods described in the book. The resulting empty weight is entered into the performance spreadsheet.

The central calculation of the spreadsheet is the sizing analysis (determination of the aircraft total weight required to carry the intended payload over the desired distance and speed). This is done parametrically, by taking five guessed values of aircraft total takeoff gross weight (Wo) and for each, calculating the takeoff weight as the sum of the payload, crew, empty weight, and calculated fuel weight.

Fuel weight is determined using the Breguet Range Equation with an adjustment for fuel used during takeoff and climb. The Breguet equation actually calculates the *remaining* weight of the aircraft after the cruise, so the weight fraction of the fuel that was burned is found as one minus the fraction found using the equation.

Fuel Fraction:

$$W_f / W_0 = 1 - 0.975 e^{\frac{-R\,c_{bhp}}{550\eta_p L/D}}$$

The 0.975 term is an approximate allowance for additional fuel used during takeoff, climb, descend, and landing, suitable for most homebuilts.

Sizing results are graphed in the format "guess weight vs. calculated weight." The correct answer occurs where they are the same, which can be seen on the graph at the intersection of a line connected the calculated points with a line at 45 degrees from the origin (shown in the example below).

As a learning experience, the user is required to read off the sizing result (intersection of the lines) and enter this result back in the spreadsheet. From this result, a variety of design parameters are calculated including wing area and geometry, tail geometry, and required engine size.

After layout of the design, the user enters additional input parameters that are used for performance calculations. These include maximum speed, cruise speed, rate of climb, takeoff distance, and cruising range. All are determined from standard equations as described in the references. Speed and rate of climb are graphed versus velocity.

Finally, an aspect ratio optimization is provided. Aspect ratio is parametrically varied and resulting changes in range and performance are graphed. The user is encouraged to inspect the graph for a more-optimal aspect ratio that meets performance requirements.

This spreadsheet can be viewed and downloaded at the author's website *(www.aircraftdesign.com)*. Note that the spreadsheet is posted as "shareware", and a registration fee is expected if the program is being used.

SAMPLE AIRCRAFT DESIGN AND ANALYSIS

For the simplified design book for homebuilders, a rather unique asymmetrical design was conceived and used as an illustrative example. Shown in figure 1 below, this aircraft resembles a standard single engine general aviation design but with an extra engine placed out on one wing, in a pusher arrangement. This minimizes engine-out control problems in an otherwise-normal homebuilt aircraft.

Based on the initial design sketch and the range and payload requirement, the initial sizing inputs were prepared as follows:

Inputs		
Stall speed	(kts)	60
Takeoff air density	(slugs/ft^3)	0.00238
Wing CLmax		1.6
power loading	(lb/hp)	8.3333

Swet/Sref		4.2
Cfe		0.0053
Aspect ratio (A)		10
Cruise air density	(slugs/ft^3)	0.00176
Cruise velocity	(kts)	180
Engine SFC	(lb/hour /bhp)	0.45
Prop Efficiency (cruise)		0.75
Range	(nmi)	800
Fuel allowance	(%)	6
Empty Weight constant "a"		1.2438
Weight - crew	(lbs)	180
Weight - Passengers	(lbs)	180
Weight - payload	(lbs)	20

These inputs resulted in calculated values as follows:

Calculated Values		
Stall speed	(ft/sec)	101.3
Dynamic pressure	(psf)	12.2
Wing loading (W/S)	(psf)	19.55

Wo	(lb)	2000.0
Wing Area	(sq ft)	102.3

Cdo		0.0223
K (=1/piAe)		0.0424
W/S cruise		19.2
Cruise velocity	(ft/sec)	304.0
Dynamic pressure	(psf)	81.3
L/D cruise		9.57
Engine SFC	(lb/sec /bhp)	0.000125
Range	(ft)	4860800
Breguet Exponent		0.1539
Wf/Wo		0.1641
Wf/Wo with allow.		0.1739

The sizing calculations are below, showing five guessed values of takeoff gross weight (Wo) and the resulting empty weight and calculated takeoff gross weight. By inspection one call tell that the correct answer must be just under 2000 lbs. These results are graphed in figure 2 below, showing the correct answer at about 1950 lbs. This was rounded to 2000 lbs for subsequent design layout.

Wo guess	We/Wo	We	Wo calculated
1000	0.6680	668.0	2403.2
1500	0.6440	966.0	2087.3
2000	0.6276	1255.1	1914.2
2500	0.6151	1537.7	1801.0

From this sizing result the spreadsheet calculated the size of engine required based on a power loading input, as follows.

Enter Wo from graph	(lbs)	2000
Pick engine with horsepower of at lea		120

Now find a suitable engine of at least this horsepower and enter its power below:

Power of Selected Engine:	120
Calculated Power Loading:	8.33

Wing and tail geometries were calculated from the sizing results and a few more inputs, as follows:

Wing Span	(ft)	31.98
Root Chord	(ft)	4.26
Tip Chord	(ft)	2.13
Mean Chord	(ft)	3.32
Tail areas:		
Sht (horizontal)	(sq ft)	20.35
Svt (vertical)	(sq ft)	13.08

After design layout was completed, previous inputs were updated as needed and additional inputs were provided for performance calculations, as follows:

Other Inputs		
Propeller Diameter	(ft)	5
Engine RPM	(rev/min)	2700
Cooling Power Loss	(%)	6
Cruise Power Setting	(% of SL hp)	62
Cruise air density	(slug/ft^3)	0.00176

Cruise speed	(kts)	180
Cruise Prop efficiency		0.85

Some of the performance results are tabulated as shown below. Of particular interest is the calculated range of 964 nautical miles. This is somewhat greater than the initial sizing required range of 800 nmi. Recall that the selected Wo of 2000 lbs was higher than the actual sizing result.

Calculated Values		
wing loading (W/S)	(psf)	19.55
stall speed	(ft/sec)	101.34
stall speed	(kts)	60.00
power loading	(lb/hp)	8.33
Takeoff Parameter		123.2
Takeoff Groundroll	(ft)	874.2
Takeoff to 50 ft	(ft)	1159.1

Cruise speed	(ft/sec)	304.02
Cruise Advance Ratio J		1.3512
Cruise q	(psf)	81.3
Cruise W/S	(psf)	19.2
Cruise L/D		9.6
Wfuel (total)	(lbs)	365
Wfuel (usable)	(lbs)	344
Wfuel (cruise)	(lbs)	294
log term		1.177691
Range	(ft)	5854552
Range	**(nmi)**	**964**

Maximum and cruise speeds are graphed in figure 3. Rate of Climb at sea level is shown as figure 4. The weight and balance report is shown in figure 5, but recall that the spreadsheet does not actually estimate the component weights, it only sums them from user inputs. Component weight estimation may be added to the spreadsheet in the future.

Finally, an aspect ratio optimization was calculated by the spreadsheet as shown in figure 6. The program parametrically varied the aspect ratio and recalculated weight and performance. For this design, the optimal answer is the lowest aspect ratio meeting all performance requirements (roughly 9.7). While normally one thinks of a higher aspect ratio as being more optimal, in this case the baseline aspect ratio is already high enough that its reduction saves enough structural weight to yield a net improvement in the design. If aspect ratio is lowered even further, though, the cruise speed starts to suffer due to the increase in the induced drag.

COMPARISON TO RDS RESULTS

The same design was modeled in the RDS-Professional program for comparison sake. This begs the question – are the RDS results valid enough for benchmarking purposes? RDS verification has been reported in several presentations such as Raymer[5]. RDS has been used by industry for many years and calibrated in several non-published internal evaluations, with good success. Finally, RDS is based on time-honored classical analysis methods as described in ref. 4. Hopefully, they work.

The first comparison (figure 7) shows total drag during level cruise at 10,000 ft. This shows fairly good agreement, considering the simplicity of the spreadsheet analysis and the paucity of input data.

Thrust as estimated by the methods in RDS is shown in figure 8. This shows remarkable agreement with the cruise thrust at 10,000 ft as shown in figure 3. Rate of Climb at sea level shows fair agreement (figure 9).

The final comparison is that of range. This is fairly close – 937 nmi versus the spreadsheet result of 964 nmi (3% difference).

COMMENTS ON CODING AND OPERATION

Creation and improvement of this Excel™ spreadsheet took about 80 hours. This compares to the thousands of hours represented in RDS-Professional or similar programs. Some of the time savings can be attributed to the ease of setting up input, output, and graphing within the spreadsheet environment. Most of the coding savings, though, are the result of the simplicity of the methods employed. Such a spreadsheet simply cannot operate with the flexibility or accuracy of a sophisticated program like RDS.

To size and analyze a new design takes under 30 minutes, for an experienced user. Again, this compares favorably with RDS wherein it takes 1 to 6 hours to set up a new design model for analysis. Again, most of the difference is due to the simplicity of the analysis. Also, RDS and similar codes have legions of capabilities and outputs not seen in the simple spreadsheet, and can be used for virtually all types of aerospace vehicles. The spreadsheet is limited to piston-props typical of homebuilts.

SUMMARY & CONCLUSIONS

An Excel™ spreadsheet was created for initial aircraft sizing and performance analysis, using simplified methods and minimal inputs.

Based on the sample case described above, one can conclude that the results of such a spreadsheet are fairly reasonable for a normal piston-prop design such as tested herein. Such a spreadsheet code is very easy to operate, but the results cannot be expected to compete with a full-blown aircraft design program.

FIGURES:

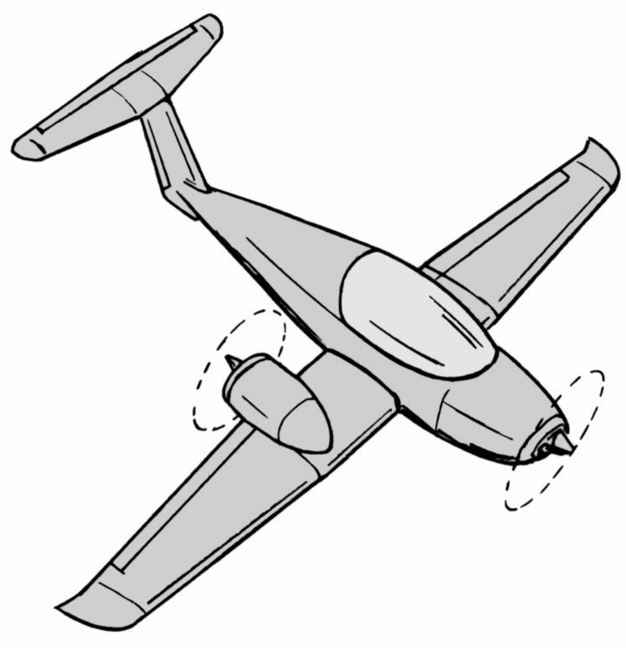

figure 1. DR-4 Asymmetric Twin

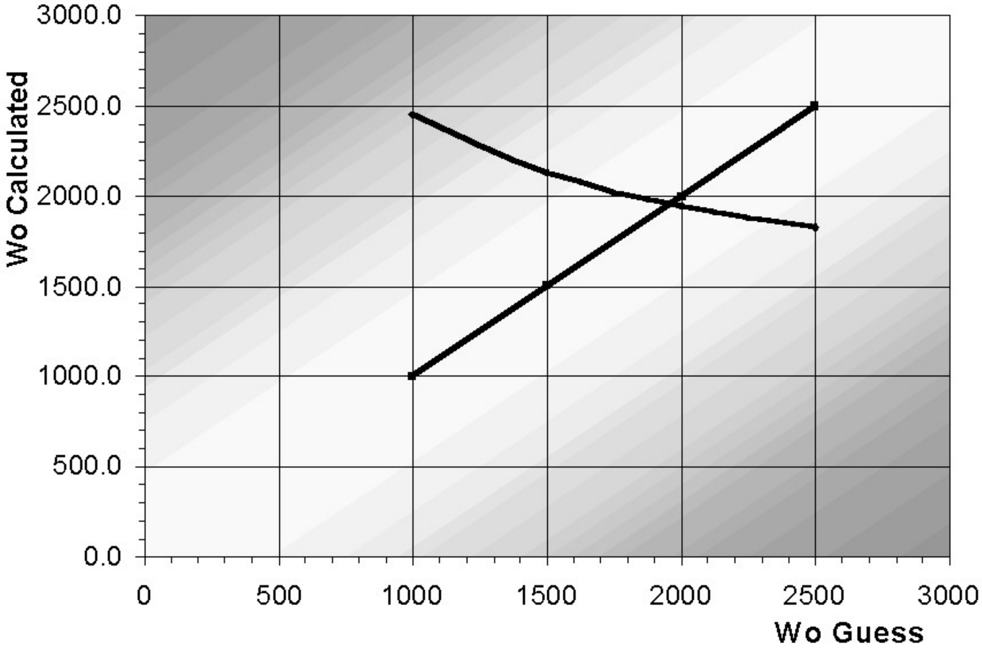

figure 2. Sizing Graph

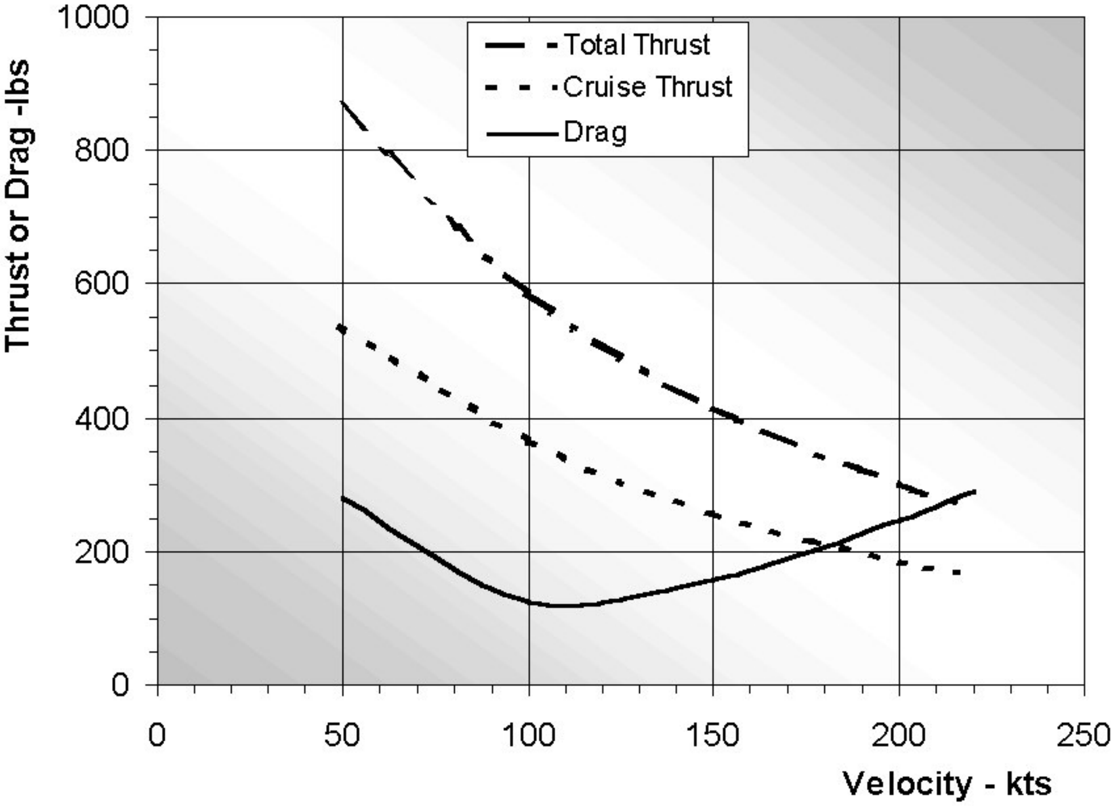

figure 3. *Maximum and Cruise Speeds*

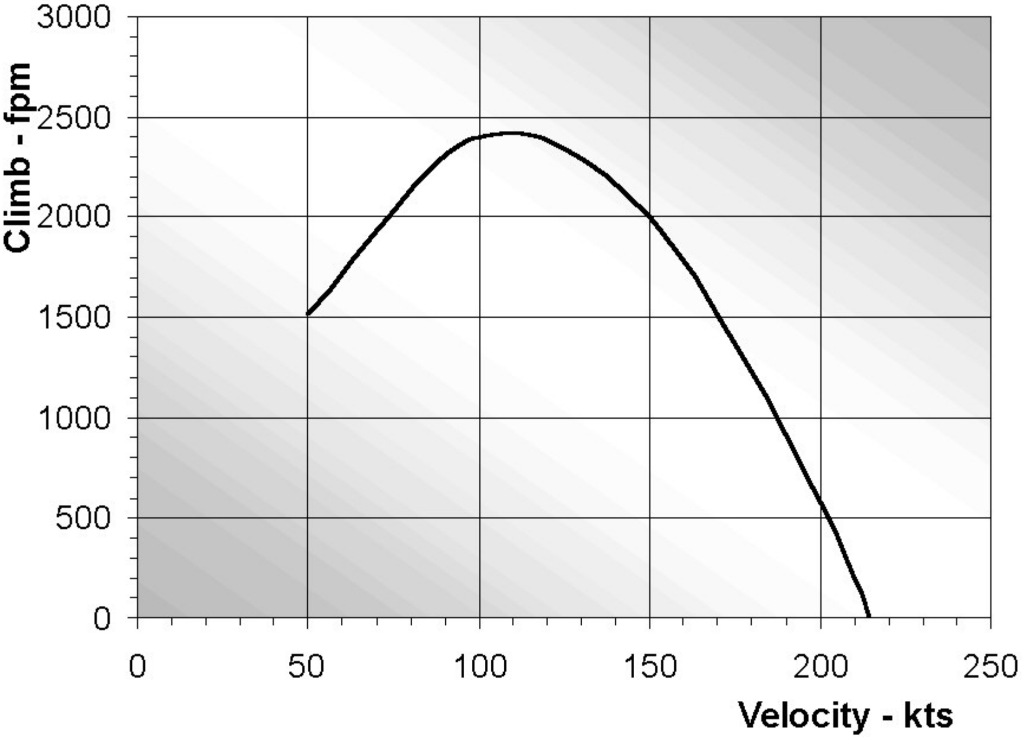

figure 4. *Rate of Climb*

	Weight lbs	Loc ft	Moment ft-lbs
STRUCTURES	**661.0**		**5600**
Wing	276	6.5	1794
Horizontal Tail	24	21.0	504
Vertical Tail	18	19.0	342
Ventral Tail	8	17.0	136
Fuselage	155	9.0	1395
Canopy	15	8.0	120
Nacelle on wing	50	9.0	450
Nacelle/cowling	30	7.5	225
Motor Mount	10	7.5	75
Main Landing Gear	56	9.0	504
Nose Landing Gear	19	2.9	55
PROPULSION	**411.0**		**2877**
Engine	340	7.0	2380
Air Induction	3	7.0	21
Cooling	3	7.0	21
Exhaust	8	7.0	56
Engine Controls	2	7.0	14
Misc. Engine Inst	5	7.0	35
Propeller	30	7.0	210
Starter	10	7.0	70
Fuel System	10	7.0	70

	Weight lbs	Loc ft	Moment ft-lbs
EQUIPMENT	**69.0**		429
Flight Controls	10	5.5	55
Instruments	10	5.5	55
Hydraulics	2	6.0	12
Electrical	12	6.0	72
Avionics	15	5.0	75
Air Conditioning			0
Anti-Icing			0
Furnishings & Equipment	20	8.0	160
(% We Allowance)	10		
Empty Weight Allowance	114.1	7.8	891
TOTAL WEIGHT EMPTY	**1255.1**	**7.8**	9797
USEFUL LOAD	**744.9**		
Crew	180.0	8.0	1440
Fuel	358.9	7.5	2692
Oil	6	5.0	30
Passengers	180	8.0	1440
Payload	20	10.0	200
TAKEOFF GROSS WEIGHT	**2000.0**	**7.8**	15598

Possible Loading Conditions	Crew+Pass+Pld, No Fuel	1641.1	7.9	12907
	Crew+Pass,No Pld,No Fuel	1621.1	7.8	12707
	Crew only, No Fuel	1441.1	7.8	11267
	Crew only, Full Fuel	1800.0	7.8	13958

figure 5. Weight & Balance Report

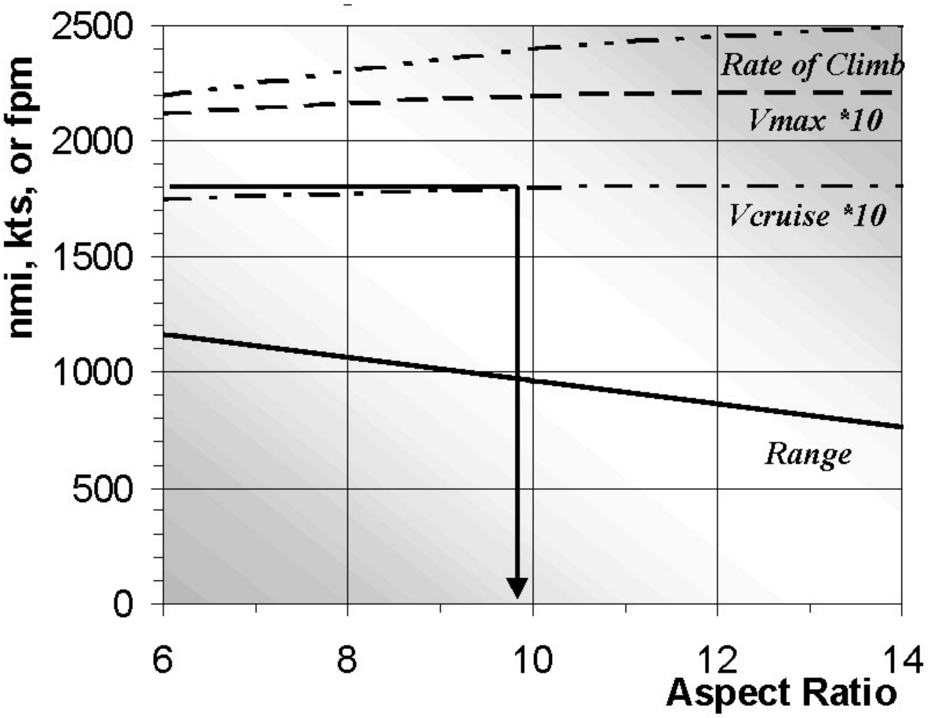

figure 6. Aspect Ratio Optimization

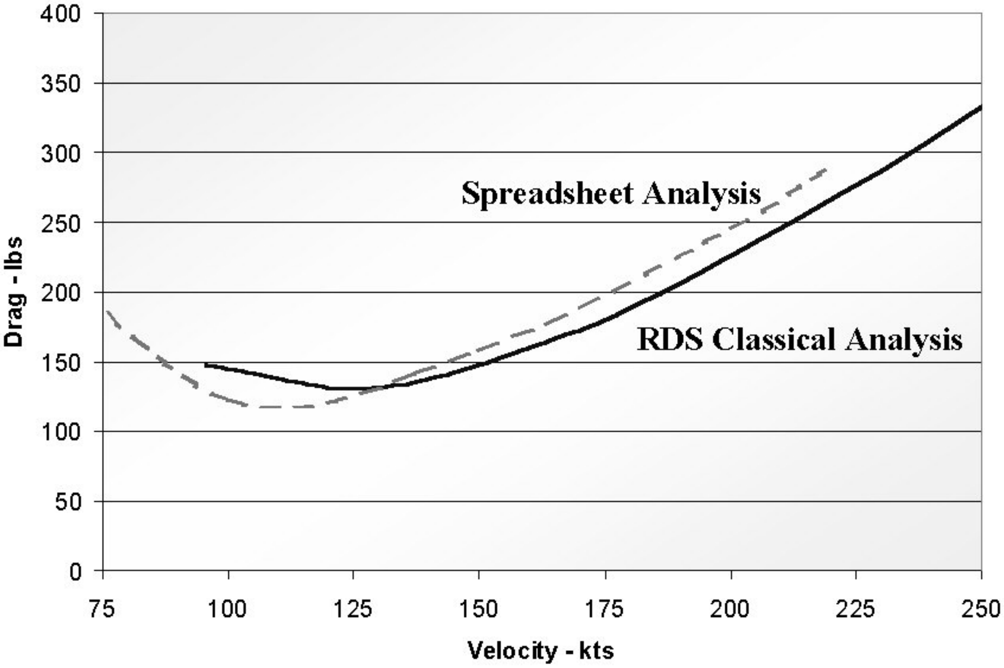

figure 7. Level Flight Drag Comparison

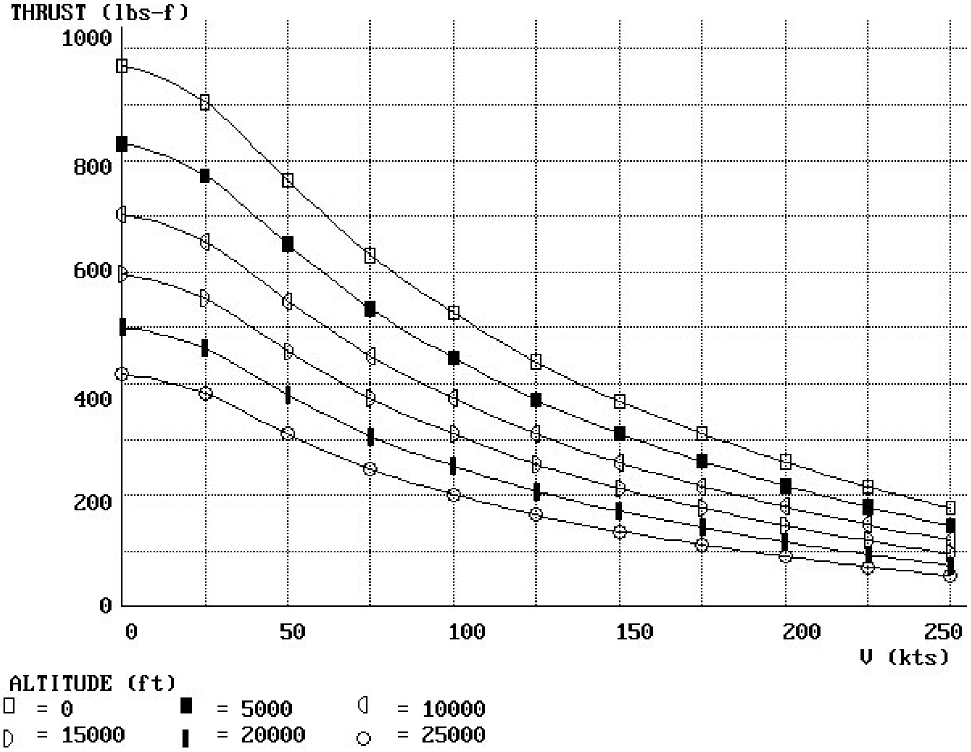

figure 8. Thrust (RDS estimate)

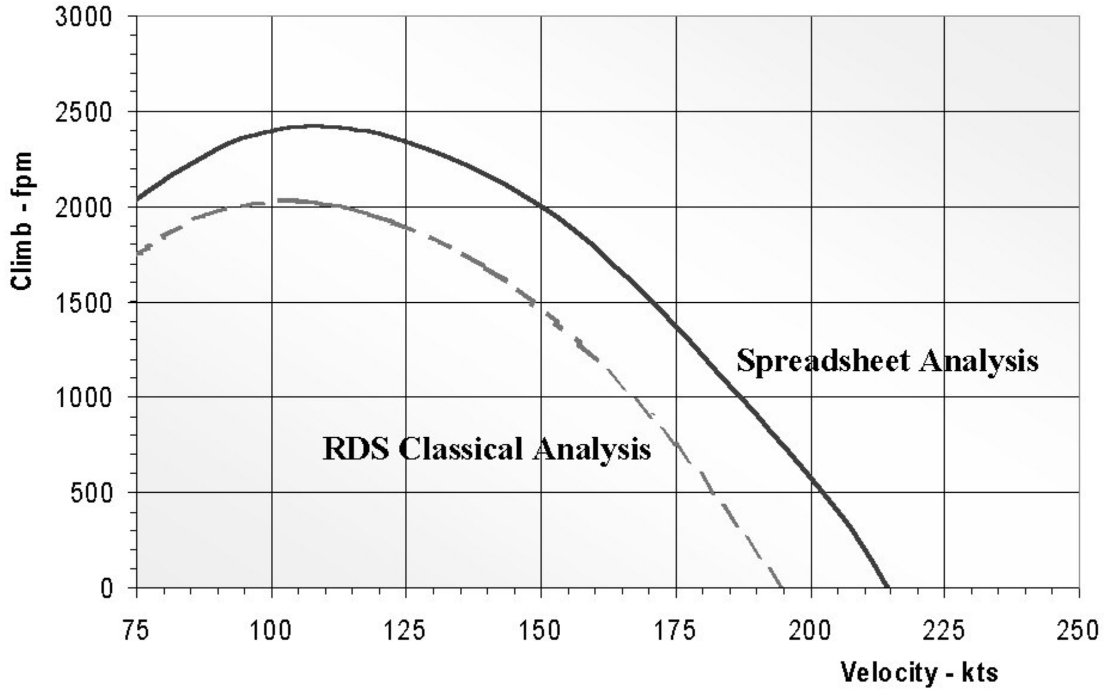

figure 9. Rate of Climb Comparison

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