IJRAME

ISSN (ONLINE): 2321-3051

INTERNATIONAL JOURNAL OF RESEARCH IN AERONAUTICAL AND MECHANICAL ENGINEERING

Transport Aircraft Weight Estimation as a Function of Range and Number of Passengers

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Abstract

Estimation of maximum take-off weight (MTOW) is the first step in conceptual design phase. Zero-order sizing methodology, which is found in most textbooks, is the general technique used for that estimation. MOTW estimation by these methods can yield results that are between 10-15% of the actual MTOW. Payload-Range is another methodology used for civil aircraft weight estimation. It is based on statistics that correlates the number of passengers (3-class) with aircraft mission range. MTOW estimation is carried out by regressing an empirical equation. This paper presents a new empirical formula as a function of number of passengers (1-class) and mission range. This methodology uses both techniques with some modifications to them. The results show fast and accurate MTOW estimation with average accuracy of 5-10%.

***Keywords**:* Aircraft design, aircraft weight estimation, conceptual MTOW estimation.

Nomenclatures

$N_{pas} = number\ of\ passengers$

$R = flight\ range$

$W_c = crew\ weight$

$W_e = empty\ weight$

Vol.2 Issue.5,
May 2014.
Pgs: 90-96

$W_f = fuel\ weight$

$W_{pay} = payload\ weight$

$W_{to} = maximum\ takeoff\ weight$

$W_{zf} = zero - fuel\ weight$

1. Introduction

Through the whole life-cycle of the aircraft design, only one parameter is the most important and that is the maximum take-off weight (MTOW). Estimation of MTOW is the first step in conceptual design phase. The word "estimation" means being able to arrive at a figure of MTOW that can be used to some degree of acceptability in the early phases of the design. Accuracy between 10-15% (Monroe *et al.*, 1998) is usually acceptable. The first estimation of MTOW is done using an existing methodology or perhaps, several different methodologies and by comparing the results. These methodologies are often taken from industry, textbooks, or from designers' notes. "*The challenge here is to reduce often non-specific requirements to quantifiable forms. The weight fraction method and some associated rules of thumb will help do that.*" (Sadraey, 2012). Estimation is based on other aircraft data with similar configuration and mission requirements. More specifically, the past history and experience plays a major role, and is a source information. Aircraft manufacturers have their own design techniques and estimation techniques that can yield the required MTOW estimates. After the conceptual phase and during the preliminary phase a lot of variables and their values are known, this helps in obtaining a better estimate of MTOW, the figure in the conceptual phase being improved to between 5-10%. Due to the fact that the aircraft design is an iterative process in nature, MTOW is constantly updated as a new more up to date data are made available.

2. Zero-Order Sizing Methodology

The MTOW (W_{to}) is estimated using the general technique found in most textbooks (Jenkinson *et al.*, 1999), (Raymer, 2006) by breaking it down into several sub-elemental weights. Some of them are evaluated based on statistics, and others are evaluated by performance equations. For transport aircraft, these sub-categories are: Empty weight (W_e), Crew weight (W_c), Payload weight (W_{pay}), and Fuel weight (W_f) giving the total weight as:

$$W_{to} = W_e + W_c + W_{pay} + W_f \qquad (1)$$

The crew weight (W_c) and payload weight (W_{pay}) are known as the useful load which includes crew, payload, and operational items. Jenkinson (Jenkinson & Marchman, 2003) stated that "*One of the main difficulties in the analysis at this stage is the variability of definitions used for mass components in published data on existing aircraft*". This useful load can be easily evaluated from the given requirements either by customer or from standard FAA (FAA website). The empty weight (W_e) and fuel weight (W_f) are both functions of MTOW. To simplify the calculation, both fuel weight and empty weight are expressed as fractions of the MTOW. Hence, rewrite Equation (1) as:

$$W_{to} = \left(\frac{W_e}{W_{to}}\right) \times W_{to} + W_c + W_{pay} + \left(\frac{W_f}{W_{to}}\right) \times W_{to} \qquad (2)$$

Solving for W_{to}:

$$W_{to} = \frac{W_c + W_{pay}}{1 - \left(\frac{W_e}{W_{to}}\right) - \left(\frac{W_f}{W_{to}}\right)} \qquad (3)$$

Empty weight fraction ($\frac{W_e}{W_{to}}$) is estimated by empirically. Although it varies for different types of aircraft and for different operational profiles, the data from existing aircraft is a good source for making this estimation. A nice estimation for this fraction was given by Jenkinson (Jenkinson & Marchman, 2003) for transport aircraft. It is equal to 0.55 for two engines and 0.47 for more than two engines. Fuel fraction ($\frac{W_f}{W_{to}}$) is crudely estimated from the modified Brequet range equation. The mission profile for civil aircraft consists of several segments (taxi, take-off, climb, cruise, etc.). Fuel fraction for each segment must be evaluated and then summed. This fraction during cruise segment makes a base for estimating the required fuel weight and fuel fraction during a flight operation. Other segments consist of less than 5% of the fuel weight burned. More details are found in many aircraft design textbooks (Sadraey, 2012), (Jenkinson *et al.*, 1999), (Raymer, 2006), etc.

3. Payload-Range Methodology

As mentioned before, the past history plays the major role as a source of information. Examination of the current aircrafts weight and geometry allows the designer to easily identify parameters of the aircraft design under consideration. The two most significant parameters that represent civil aircraft are payload and range. These parameters are the basic requirements that need to be fulfilled in new aircraft designs. From Equation (1) with keeping MTOW constant, the designer can reduce the number of passengers to increase the fuel weight to extend the flying distance (range) and vice versa. Data on current aircraft reveals that as the range is increased the MTOW increases appropriately, this is due to the additional fuel required to fulfil the mission. Kundu (Kundu, 2010) developed a linear relationship between number of passengers and MTOW for different ranges. The estimation of MTOW for in-between ranges is interpolated. For example, for 300 passengers and 5000nm range, the estimated MTOW is interpolated to be 225000 kg for a 3-class passenger seat plan.

4. New Estimation Technique

To overcome the drawback of payload-range methodology and to eliminate interpolation, a new direct relationship to estimate aircraft MTOW has been developed based on number of passengers (1-class) and mission range. Initially, Equation (1) can be re-written as:

$$W_{to} = W_{zf} + W_f \tag{4}$$

Where: $W_{zf} = W_e + W_c + W_{pay}$ = zero-fuel weight.

As mentioned before, W_c & W_{pay} are known. The empty weight (W_e) is dependent mainly on the aircraft size which in turn dependent on number of passengers. Published data of the zero-fuel weight for the current aircraft are plotted against their number of passengers (1-class) as shown in **Figure 1**. The following formula represents this relationship:

$$W_{zf} = 267600 \times e^{-\left((N_{pas}-679.7)/414.4\right)^2} \tag{5}$$

Where: N_{pas} = number of passengers.

Vol.2 Issue.5,
May 2014.
Pgs: 90-96

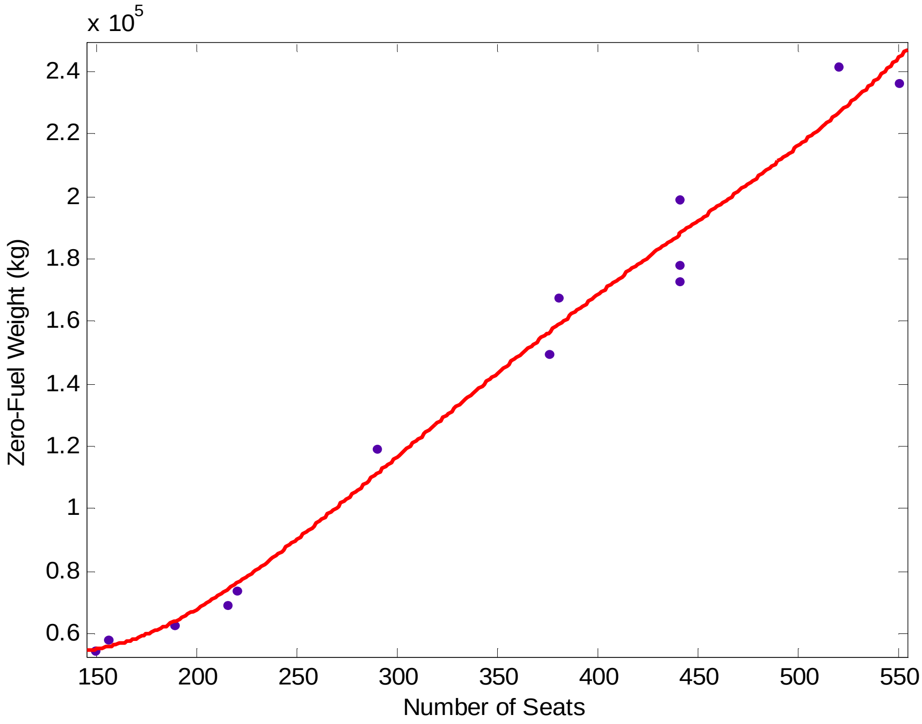

Figure 1- Zero-Fuel Weight vs. Number of Passengers

Mission cruise distance is the major parameter that is employed to evaluate the fuel weight. Also, aircraft size plays another important parameter affecting the amount of fuel required, i.e. large aircraft needs bigger engines to fly, and in turn much fuel to burn. Therefore, fuel weight is a function of range and MTOW. Rewriting Equation (4) for fuel weight as a fraction of MTOW:

$$W_{to} = W_{zf} + \frac{W_f}{W_{to}} \times W_{to} \qquad (6)$$

Solving for W_{to}:

$$W_{to} = \frac{W_{zf}}{1-\frac{W_f}{W_{to}}} \qquad (7)$$

Figure 2 shows the relationship between the range and fuel fraction for the existing aircraft. This graph was represented by the formula:

$$\frac{W_f}{W_{to}} = 0.003246 \times R^{0.4822} \tag{8}$$

Where R = range (km).

After substituting (5) & (8) in (7) yields:

$$W_{to} = \frac{267600 \times e^{-((N_{pas}-679.7)/414.4)^2}}{1-0.003246 \times R^{0.4822}} \tag{9}$$

Where: R in km.

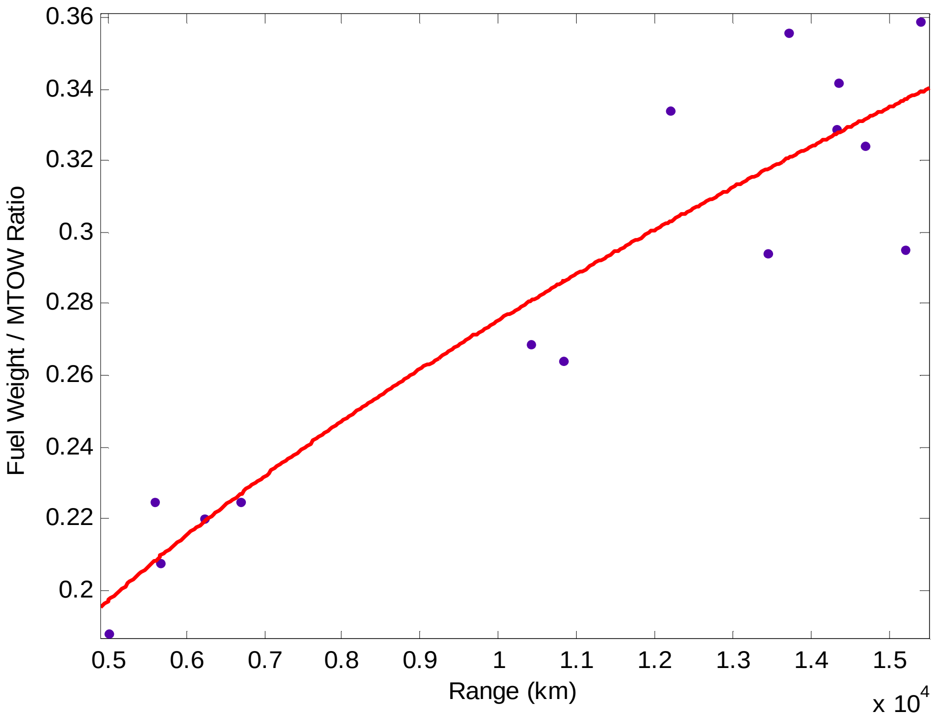

Figure 2- Fuel Weight/MTOW Ratio vs. Range

5. Results

Equation (9) has been applied for many existing transport aircraft. **Table 1** shows these results. In the 41 aircraft under consideration, 39 aircraft (95%) have accuracy better than 10% and 19 aircraft (46%) have accuracy better than 5%. Only two aircraft (5%) have 10-15% accuracy. This methodology seems to be fast and good accurate as a first MTOW estimation.

Aircraft	Input Variables		Published MTOW (kg)	Calculated MTOW (kg)	Accuracy %
	No. of Passenger	Range (km)			
A319-100	156	6700	75500	70110	- 7.14
A321-200	220	5600	95510	98741	+ 3.35
A330-200	380	13430	238000	232321	- 2.59
A330-300	440	10830	235000	268190	+ 14.04
A340-300	440	13700	276500	282376	+ 2.17
A340-600	520	14350	368000	342938	- 7.29
737-700	149	6230	70305	66487	- 5.71
737-800	189	5665	79245	83297	+ 5.11
737-900ER	215	4996	85100	94793	+ 11.4
747-200B	539	12700	351500	345185	- 1.83
747-400ER	660	14200	412775	396297	- 4.16
767-200ER	290	12200	179625	158613	- 13.24
767-300ER	350	11065	186880	199937	+ 6.99
767-400ER	375	10415	204570	216681	+ 5.91
777-200ER	440	14310	297550	284785	- 4.49
777-300ER	550	14690	351500	363030	+ 3.27
DC-9-20	90	2974	44500	41728	- 6.71
DC-9-30	115	3095	49090	49539	+ 0.81
DC-9-40	125	2880	51700	52544	+ 1.55
DC-9-50	135	3326	54900	56744	+ 3.28
DC-10-15	399	7000	206385	220216	+ 6.69
DC-10-30	399	10622	259459	236100	- 9.91
DC-10-40	399	9254	251701	230237	- 9.34
L-049	81	3685	39122	39999	+ 2.30
L-1049C	106	8288	54431	52604	- 3.42
L-1011-1	400	6667	200000	211189	+ 5.60
CS-100	125	5463	58151	56160	- 3.57
CS-300	145	5463	63322	63758	+ 0.63
CRJ-700	70	3200	34019	36526	+ 7.35
CRJ-900	86	2950	37421	40565	+ 8.29
CRJ-1000	100	2845	41640	44505	+ 6.97
MD-82/88	172	3800	67800	72111	+ 6.34
MD-87	139	4390	63500	59854	- 6.19
MD-90-30	172	3860	70760	72226	+ 2.07
F70	85	3410	41730	40819	- 2.21
F100-620	107	2450	43090	46072	+ 6.98
F100-650	107	3170	45810	47084	+ 2.84
E-170	78	3885	37200	39377	+ 5.85
E-175	86	3885	38790	41632	+ 7.33
E-190	106	4260	50300	48159	- 4.44
E-195	118	3330	50790	50860	+ 0.14

Table 1- MTOW Estimation for Current Aircraft

6. Conclusions

Estimation of MTOW is the first step in conceptual design phase. Zero-order sizing methodology which is found in most textbooks, is the general technique used for that estimation. The result of this methodology produces estimates that are between 10-15% accurate. Payload-Range is another methodology used for civil aircraft weight estimation. This paper presents a new method which uses number of passengers (1-class) and mission range. The methodology uses both techniques with some modifications to them. The results show good MTOW estimation with average accuracy of 5-10%.

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