Improved Model for Small-scale Turbofan Engine Weight Estimation

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Abstract: Weight estimation plays a crucial role at the initial stages of gas turbine development. A number of weight estimation models are described in the open sources, but design data available at these stages is scarce, so these models tend to have low accuracy. This study examines the features of available models and proposes improved weight estimation model. The database of the existing 50 turbofans with thrust lower than 50kN was developed to compare models with the statistical information, and to update the regression coefficients of the proposed model. Standard deviations and correlation factors of models were determined. Refining of model coefficients was obtained as a result of minimization of a standard deviation value.

1 INTRODUCTION

Gas turbine weight estimation is necessary for assessment of technical and economic efficiency of aircraft and engine cycle optimization at the stage of concept designing. Using this model more adequate solution accounted main restrictions can be obtained.

Analysis of turbofan engine weight models of authors such as Torenbeek E., Raymer D. P., Jenkinson L. R., Svoboda C., Clavier J., Guha A., Byerley A. R. and Kuzmichev V. S., showed that with respect to small-scale engines, they give poor accuracy (Kuz'michev, 2018).

At the present day small-scale turbofan engines are widely adopted. These engines are used for light aeroplanes, UAVs, cruising missiles, and as the auxiliary power plants. They may also be converted for use with distributed propulsion.

The regression models of turbofan engine weight based on statistical data of existing advanced gas turbine engines are used at the conceptual design stage. The accuracy of these models depends on the amount and adequacy of available information on existing engines.

Current regression weight models should be constantly refined considering modern design and technological solutions in gas turbine industry. This fact defines the relevance of this study. Targeting the small-scale gas turbine engines is the particularity of the presented study. The objective of this work is to increase the accuracy of the weight model of small-size scale turbofan engines by refining the empirical coefficients.

2 WEIGHT MODEL

In the article, Kuz'michev gas turbine weight model (Kuz'michev, 1991) developed at Aircraft Engine Theory Department of Samara University is considered. Model refining is proposed to increase model accuracy of weight assessment at initial stage of aircraft engine designing. The weight model depends on 5 engine workflow parameters:

$$\left(W_{\text{eng}} = f\left(BPR,\ OPR,\ G_{22\text{corr}},\ T_4\ ,\ FPR\right)\right). \quad (1)$$

In General, the weight is calculated by expression:

$$W_{\text{eng}} = \left(W_{\text{PF}} + W_{\text{SF}} + W_{\text{mixer}} + W_{\text{ab}}\right) k_{\text{e}} k_{\text{lf}} \quad (2)$$

where:

- $W_{\text{PF}} = B\left(G_{22\text{corr}}\right)^{k_1}\left[\left(\dfrac{OPR}{FPR}\right)^{0,286} - 1\right]^{k_2} k_{T_4}$ – weight of the engine core;
- $G_{22\text{corr}} = G_{21\text{corr}}\dfrac{1}{FPR}\sqrt{1+\left(FPR^{0,286}-1\right)\dfrac{1}{\eta_{\text{F}}}}$ – corrected mass flow rate at the primary flow fan exit;
- $G_{21\text{corr}}$ – corrected mass flow rate at station 21;º
- $W_{\text{SF}} = 2,865 \cdot G_{\Sigma\ \text{t-o}}^{0,903} BPR^{0,104} FPR^{1,193}$ – weight of the fan, fan turbine and bypass duct;
- $W_{\text{mixer}} = 2,316 \cdot G_{\Sigma\ \text{t-o}}^{0,753}$ – weight of the mixer duct (if presented);

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Table 1: Values of coefficients for engine weight estimation.

Type of gas turbine engine	$0{,}5 < G_{22\mathrm{corr}} < 5$ kg/s			$5 < G_{22\mathrm{corr}} < 50$ kg/s			$G_{22\mathrm{corr}} > 50$ kg/s		
	B	k_1	k_2	B	k_1	k_2	B	k_1	k_2
Turbojet, turbofan $OPR > 5$	20,9	0,8	0,5	15,2	1	0,5	6,96	1,2	0,5
Turbojet, turbofan $OPR < 5$	16,0	0,8	0	11,6	1	0	5,32	1,2	0

- $W_{\mathrm{ab}} = 2{,}9 \cdot G_{\Sigma\,\mathrm{t\text{-}o}}$ – weight of the afterburner (if presented);
- k_{e} – coefficient of engine sophistication impact (changes over the years) (Figure 1);
- k_{lf} – coefficient of engine life impact:

$$k_{\mathrm{lf}} \begin{cases} 1{,}0 \ldots 1{,}07 \ \text{– for subsonic aircraft;} \\ 1{,}0 \text{ – for military long-range aircraft;} \\ 0{,}9 \text{ – for fighters.} \end{cases} \tag{3}$$

- $k_{T_4} = 1 + 2 \cdot 10^{-4} \left(T_{4\,\mathrm{max}} - 1200 \right)$ – coefficient of turbine cooling system impact.

Values of B, k_1, k_2 were obtained statistically and are shown in Table 1. Further, these coefficients are proposed to be refined for small-scale turbofan engines taking into account enhanced statistical data.

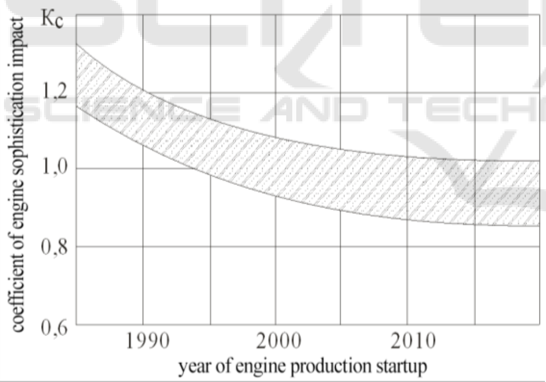

Figure 1: Coefficient of engine sophistication impact against the year of engine production startup.

3 REFINING OF EMPIRICAL COEFFICIENTS

3.1 Search and Preparation of Input Data

Dimensions of a gas turbine engine significantly influence the accuracy of weight estimation. Increasing of standard deviation is observed in case of small-scale engines due to the fact that conventional weight models were created and suitable for middle- and large-scale engines. This was primarily caused by the lack of information about the parameters of small-scale turbofan engines in public access.

In this regard, the database consisting of 151 turbofan engines with a thrust less than 50 kN was collected to provide statistical data for model refinement. It includes different types (turboprop, turbojet, turbofan) and configurations of engines for civil and military aviation. Production start date of accounted engines relate to the range from 1964 to 2018.

The search of input data was based on the analysis of works (Torenbeek, 1976; Raymer, 1992; Jenkinson, 1999; Svoboda, 2000; Lolis, 2014; Guha, 2012; Byerley, 2013; Roux, 2007; Sorkin, 2010; Skibin, 2010; Shustov, 2000). Commonly, there is no information about the cycle parameters in open access. Only 42 engines among 151 had all required cycle parameters. Basically, just basic engine features and a brief design description are presented. Quite often there is no information about the inlet turbine temperature, and if it is presented, the corresponding cross-section and mode of operation are usually not specified. Not always the information on the air mass flow rate and the overall pressure ratio is available.

Therefore, for some engines the missing information was obtained using the CAE-system ASTRA, developed at the Department of Aircraft Engine Theory of Samara University (Kuz'michev, 2017; Krupenich, 2017).

Reconstruction of the dataset by minimizing the deviation between published and calculated data provided necessary information on the thermodynamic parameters of additional 8 engines. Thus, final database of the parameters required for weight estimation includes 50 engines.

For these engines (Table 2), the empirical coefficients have been corrected. Table 3 shows that the range of cycle parameters for this dataset is quite wide.

Table 2: Main technical data of turbofan engines.

Parameter	Year	$G_{\Sigma\ t\text{-}o}$	$P_{t\text{-}o}$	*OPR*	T_4	*BPR*	W_{eng}	D_F	*FPR*
Quantity dimension	–	kg/s	kN	–	K	–	kg	m	–
Adour RT.172 Mk.811	1977	43,1	24,5	11,3	1413	0,75	738	0,559	2,7
AdourMk151 RT.172-06	1973	41,2	23,2	11	1427	1	594	0,567	2,6
AI-22	2000	125,3	36,82	15,87	1455	4,77	765	1,02	1,65
AI-222-25	2008	50,2	24,5	15,9	1480	1,19	440	0,63	1,7
AI-222-28	2014	50,6	27,47	16,9	1590	1,13	520	0,63	1,7
AI-25TL	1973	46,8	16,86	9,5	1230	1,98	400	0,985	1,7
AL-55	2007	28,5	17,26	17,5	1445	0,515	315	0,59	2,5
ALF502L	1982	116	33,4	13,7	1423	5,7	606	1,02	1,6
ALF-502R-3	1981	111	29,81	11,6	1428	5,71	576	1,27	1,6
AS907-1-1-A	2002	86,8	30,8	21	1550	4,2	619	0,87	1,8
Astafan IVG	1981	36,7	7,75	8,5	1273	9	220	0,56	1,6
ATF3-6	1981	73,5	22,9	24	1448	3	460	0,853	1,6
ATF3-6-1C	1981	73,5	22,45	21	1448	2,8	529	0,79	1,6
CF34-3A	1996	147	41,013	21	1477	6,2	737	1,118	1,44
CFE738-1	1992	108,9	26,3	23	1643	5,3	551	0,902	1,7
CFE738-1-1B	1993	109	26,35	30	1650	5,9	601	0,801	1,7
DB-730F	1966	34,5	9,37	5,5	1148	5,5	240	0,9	1,29
DV-2	1987	49,4	21,58	13,5	1463	1,46	450	0,645	2,2
F104	1978	73,5	24,2	21	1448	3	510	0,583	1,6
F106	1970	5,71	2,73	13,9	1280	1	56,7	0,32	2,1
F107-WR-100	1979	6,1	2,67	13,75	1282	1,03	58	0,305	2,08
F107-WR-101	1975	6,15	2,88	13,8	1280	1,03	64	0,305	2,1
F109-GA-100	1985	20,3	5,92	20,7	1423	5	190	0,756	1,6
F3-IHI-30	1987	34	16,37	11	1213	0,9	340	0,56	2,6
FJ44-1	1992	28,7	8,45	12,8	1291	3,28	202	0,483	1,6
FJ44-1A	1992	28,6	8,46	12,8	1350	3,28	209	0,531	1,5
JT15D	1971	33,1	9,79	10	1283	3,2	231	0,691	1,5
JT15D-5	1983	42,2	13,55	12,6	1288	3,3	287	0,521	1,6
JT15D-5D	1993	34,1	13,55	13,1	1288	3,3	284	0,686	1,8
Larzac 04-C20	1983	28,6	14,22	11,13	1433	1,038	302	0,451	2,3
Larzac 04-C6	1977	26,6	13,19	10,6	1413	1,13	280	0,451	2,3
LF507	1991	116,1	31,138	13,8	1365	5,6	628	1,272	1,45
M45-H-01	1974	108	33,73	16	1355	3	708	0,87	1,6
M88-2	1996	65	50	24,5	1850	0,3	897	0,696	3,9
Model 471-11DX	1975	5,9	2,9	13	1280	1	56,6	0,317	2,2
PW305A	1992	77,2	20,83	23	1350	4,3	450	0,87	1,8
PW305B	1990	81,6	23,39	15,5	1350	4,3	450	0,779	1,8
PW306B	1999	81,7	26,91	20,58	1460	4,24	522,1	1,138	1,57
PW308A	2001	92,6	30,74	21	1600	3,88	618	0,93	1,88
RB.199-34R-04 Mk.103	1972	73,1	40,7	23,5	1598	1,06	1061	0,734	3,4
RD-1700	2005	30	16,7	14,3	1460	0,78	297,5	0,624	2,5
RD-33	1977	77	49,5	21,7	1680	0,55	1217	0,746	3,15
TF30-PW-3	1964	105,7	47,82	17,1	1144	1,1	1769	1,346	1,87
TF34-GE-2	1972	153	42	21	1500	6,2	813	1,27	1,5
TFE731-1	1969	51,3	15,55	19	1285	2,7	272	0,716	1,5
TFE731-2	1972	51	15,9	19	1283	2,66	340	1	1,65
TFE731-3	1974	53,7	16,47	14,6	1353	2,8	343	0,716	1,54
TFE731-5	1983	65	19,16	19,4	1378	3,4	375	0,886	1,67
TFE731-60	1995	84,8	22,26	17,8	1450	3,9	448	0,78	1,7
WR19-A2	1974	5,3	2,12	7,62	1180	1,15	41	0,305	1,45

Table 3: Ranges of cycle parameters.

Parameter	$G_{\Sigma\ \text{t-o}}$, kg/s	$P_{\text{t-o}}$, kN	*OPR*	T_4, K	*BPR*	W_{eng}, kg	D_F, m	*FPR*	Year
min	20	8,45	9,8	1291	0,16	180	0,452	1,44	1992
max	1436	406	50	2273	11	7893	3,124	7	2016

3.2 Evaluation of the Weight Model Accuracy for Small-scale Turbofan Engines

The accuracy of the model may be defined as the standard deviation of the calculated and the actual values. Statistical models are considered to have a satisfactory accuracy if the standard deviation is less than 10-15%. The accuracy of weight model is evaluated by four main indicators: the standard deviation, the average relative error of the approximation, the correlation index and the Fisher criterion. These indicators allow choosing the most accurate model in their comparative analysis. They can be used to select the appropriate model. For the collected database, the standard deviation of the original model is 16%, the average approximation error was 13%, and the correlation index was 0.905. The value of the Fisher criterion is 106. The table value of the Fisher criterion at the level of significance 0.05 is 3.2. As $F_{calc} > F_{tab}$ (106 > 3,2), so the model is deemed to be statistically significant and reliable.

Analysis of the model accuracy shows that its coefficients need to be updated as the relative standard deviation of the model does not meet the required value.

3.3 Adjusting the Statistical Coefficients of the Weight Model of Small-scale Turbofan Engines

The selected engines are divided into 2 groups. The first group includes engines with the corrected air flow rate through the fan less than 10 kg/s, the second group of engines with the corrected air flow rate through the fan from 10 kg/s to 20 kg/s. This is done in order to update empirical coefficients taking into account their differences, that positively influences on the accuracy of the model. The first group included 27 engines, and the second – 23.

Using collected data empirical coefficients of the weight model for two engine groups have been refined. Adjustment was made by standard deviation minimization. New values of coefficients are presented in Table 4. According to the obtained results, graphs of actual and calculated weight deviation are presented on Figures 2-3.

Table 4: The refined values of coefficients for small-scale engine weight estimation.

Type of gas turbine engine	$0{,}5 < G_{22\text{corr}} < 10$ kg/s			$10 < G_{22\text{corr}} < 20$ kg/s		
	B	k_1	k_2	*B*	k_1	k_2
Turbojet, turbofan $\pi^*_{C\Sigma\ \text{t-o}} > 5$	15,49	0,87	0,15	6,81	1,19	0,16

Standard deviation is 14.1 percent for the first group of engines and the adjusted empirical coefficients. Standard deviation is 11.8 percent for the second group. The relative standard deviation of the model improved from 16 to 13.5 percent (the average approximation error is 10.4 percent), which satisfies the adequacy requirements. The correlation index for the updated empirical coefficients is 0.959, and the value of the Fisher criterion is 270. The critical value of the Fisher criterion at the significance level of 0.05 is 3.2, so the statistical model may be considered as statistically reliable.

4 CONCLUSIONS

This research provided the reconstructed dataset of the 50 turbofans, which was used to update the weight models, described in the open sources.

The results of this study show that Kuzmichev weight estimation has the highest accuracy, showing standard deviation of 11.8 percent for turbofan flow rates of 10 to 20 kg/s and standard deviation of 13.5 percent for the flow rates below 10 kg/s.

For the next step, authors plan to create a software based on artificial neural network to collect new data on the existing engines and update the weight model. This will allow continuous updating of empirical coefficients of the model using new statistical data.

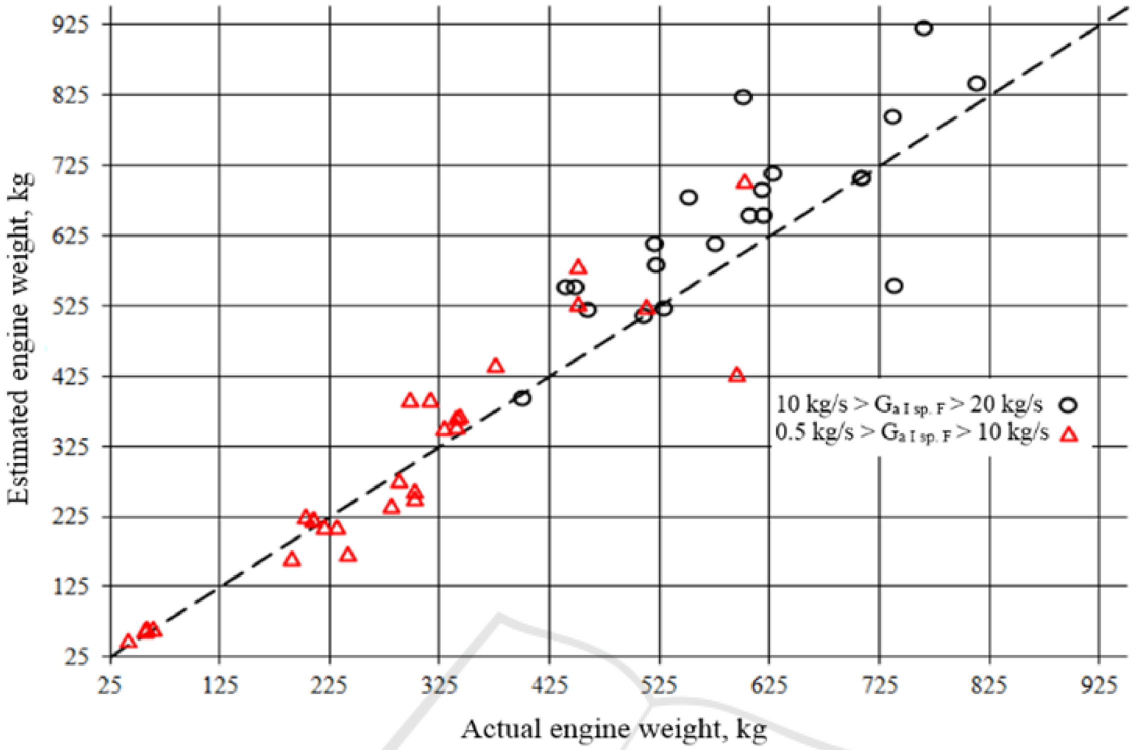

Figure 2: Deviation of actual and calculated values of engine weight for the original model.

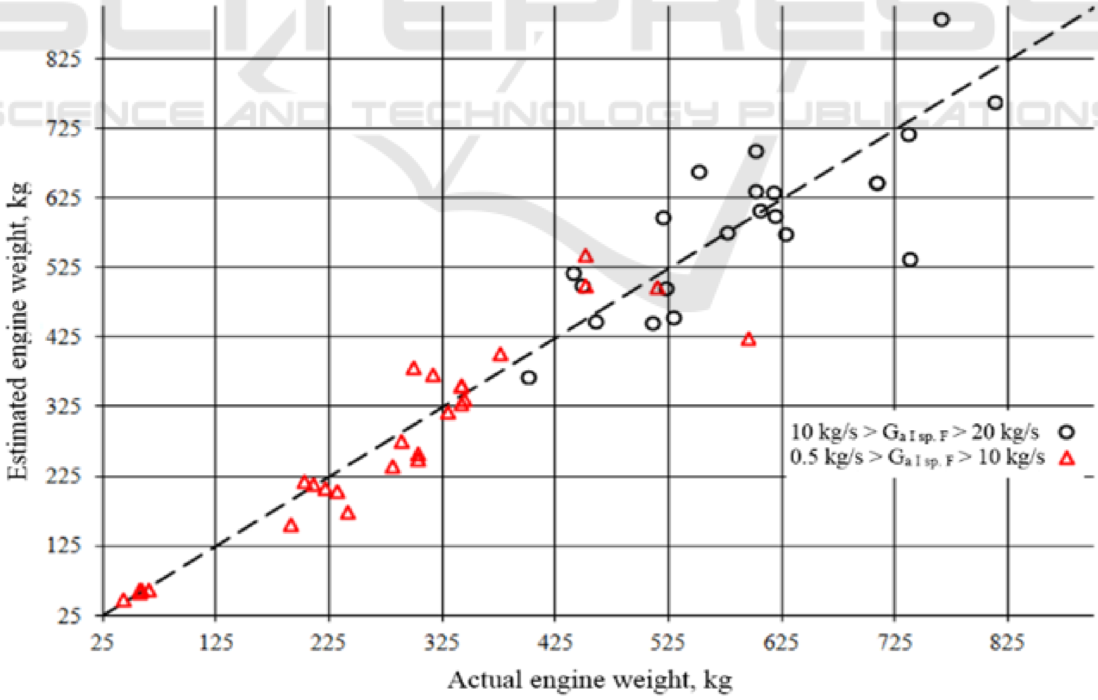

Figure 3: Deviation of actual and calculated values of engine weight for the improved model.

NOMENCLATURE

BPR = bypass ratio
D = diameter
FPR = fan pressure ratio
G = mass flow rate
OPR = overall pressure ratio
P= thrust
T = total temperature
W = weight

Subscripts

a= air
C = compressor
eng = engine
F= fan
t-o = take-off
Σ = overall
4= section after combustion chamber

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