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MASS MODEL OF MICROGASTURBINE SINGLE SPOOL TURBOJET ENGINE

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Abstract

Presented paper consists detailed mass model of micro gas turbine single spool turbojet in well-known Scheckling design layout (1R/1A). One of major criteria in aviation is weight that is granted by airworthiness requirements. At present, exempt from certification process are RC airplanes or UAV with total take-off weight less than 22.5 kg. From the 70's mass model was added as a part of aero engines design process. Engine weight affects airplane or UAV weight greatly, because it is a source of variety structure loads. Weight reduction efficiency factor, verifying in terms of design quality a micro gas turbine, and the flying object as a system. Developed computational model allows to estimate weight of the components (gas generator shaft, compressor rotor, compressor diffuser, combustor, turbine nozzle, turbine rotor, jet pipe, casings and housings) and whole engine as well. Model inputs are related to technological axi-symmetric dimensions obtained from thermo gas dynamic and construction equations, making it easy to use. Obtained results was presented for several micro gas turbines (mSO1-designed by author, FD3-64, TK-50, JF-50, MW-54, KJ-66, AMT Olympus). Advantage of this model allows to avoid time consuming CAD modelling process at design study level. Presented algorithm can be used also in the design of UAV as well as issues related to the preliminary multidisciplinary design and optimization PMDO cases.

Keywords: *gas turbine, micro gas turbine, turbojet, propulsion, mass model, Schreckling*

1. Introduction

Presented computational model is based on a prototype micro jet engine mSO-1 (Fig. 1). At the stage of the design assumptions entire design work will be simplified but similar to the commercial gas turbine projects. Model mass as part in the design process of turbine engines was introduced in the 70s of the last century. Weight reduction is one of the quality indicators of the developed solution. In the case of micro gas turbine reduction of engine weight increases the payload efficiency of UAV. It should be noted that airworthiness rules exempt for certification process flying aircraft of take-off weight below 22.5 kg.

Mass model for micro gas turbine turbojet engine was developed for the following simplifying assumptions:

- computational model corresponds to the 1R-1A design-single stage radial compressor, single stage axial turbine layout (named „Schreckling design" from the author of first successful solution),
- engine model is based on the one-dimensional axisymmetric cross section cutaway,
- input data are characteristic technological dimensions.

2. Mass model of single spool turbojet

The general form of the equation describing the weight of the micro gas turbine engine design comes from the sum of n-mass described by structural units (building blocks e.g. compressor, combustor, rotor, turbine, jet pipe):

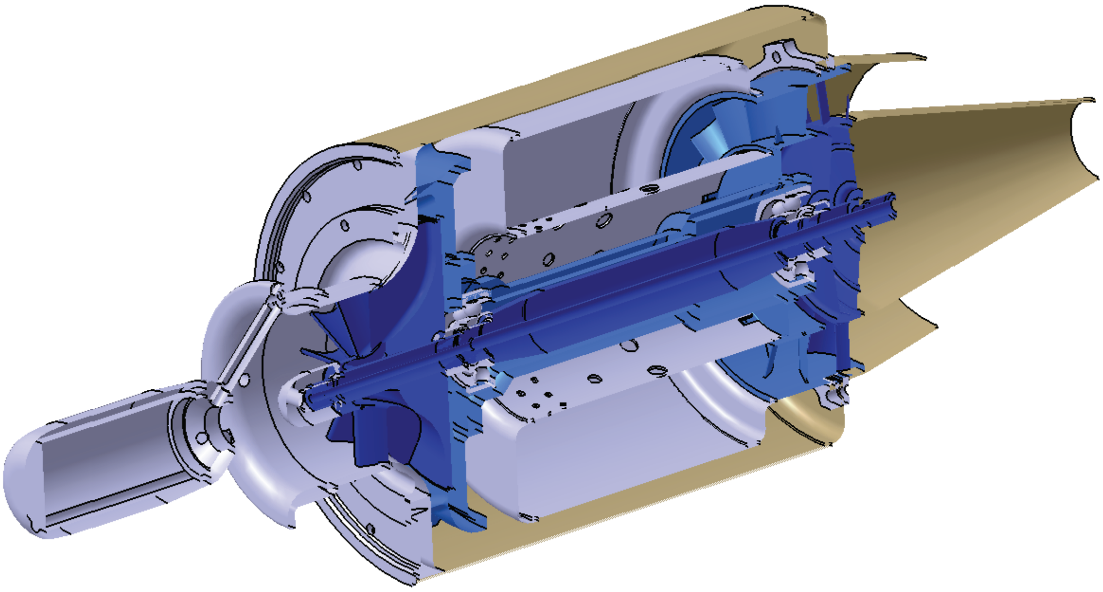

Fig. 1. Cutaway of mSO-1 turbojet engine

$$m_{KONST} = \sum_{i=1}^{n} m_n , \tag{1}$$

where:
m – mass of single structural unit,
n – number of structural unit.

Detailed description of micro gas turbine mass equation are shown below:

$$m_{KONST} = m_{SP} + m_{OW} + m_{KS} + m_{TS} + m_{DW} + m_{OB} , \tag{2}$$

where:
SP – compressor,
OW – rotor case,
KS – combustor,
TS – compressor turbine,
DW – jet pipe,
OB – external case.

Weight of the compressor unit is described by the relationship:

$$m_{SP} = m_{SPW} + m_{SPD} + m_{SPO} , \tag{3}$$

where:
SPW – compressor rotor,
SPD – compressor diffuser,
SPO – compressor case.

Weight of compressor rotor is described by equation:

$$m_{SPW} = 0.8 D_{2S} , \tag{3}$$

where:
D_{2S} – external dimension of compressor rotor (Fig. 2).

This relationship is a reasonable time saving approximation for mass estimation and is true for centrifugal design from 0.1-0.8 kg/s mass flow rate range. Approximation was verified by data included in the studies of companies Garrett and Borg Warner [1, 3] and the measurements made by the author.

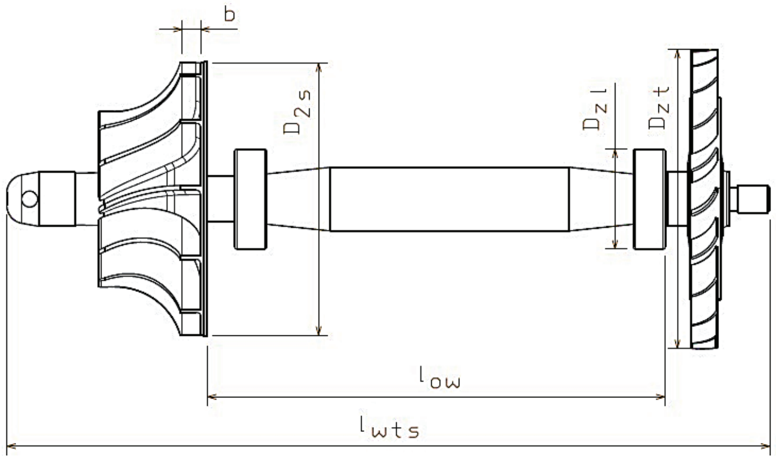

Fig. 2. Basic dimensions of mSO-1 turbojet engine rotor

Weight of the compressor diffuser is described by following equation:

$$m_{SPD} = \rho_D \cdot \left[\frac{\pi}{2} \cdot b_S \cdot \left((D_{4S} - 2 \cdot b)^2 - D_{LS}^2 \right) + b^2 \cdot (D_{3S} - D_{2S}) \cdot \sin \alpha_2 \cdot n_{LDP} + 2 \cdot b \cdot b_S^2 \cdot n_{LKS} \right], \quad (5)$$

where:
α_2 – diffuser vanes expansion angle (8–14°),
ρ_D – density of an alloy,
b_S – average wall thickness from turning process,
b – height of compressor rotor exit channel (Fig. 2),
n_{LDP} – number of diffuser vanes (9–14),
n_{LKS} – number of combustor vanes (12–36),
D_{3S} – external dimension of diffuser main body (Fig. 3),
D_{4S} – external dimension of diffuser (Fig. 3),
D_{LS} – external dimension of compressor rotor bearing.

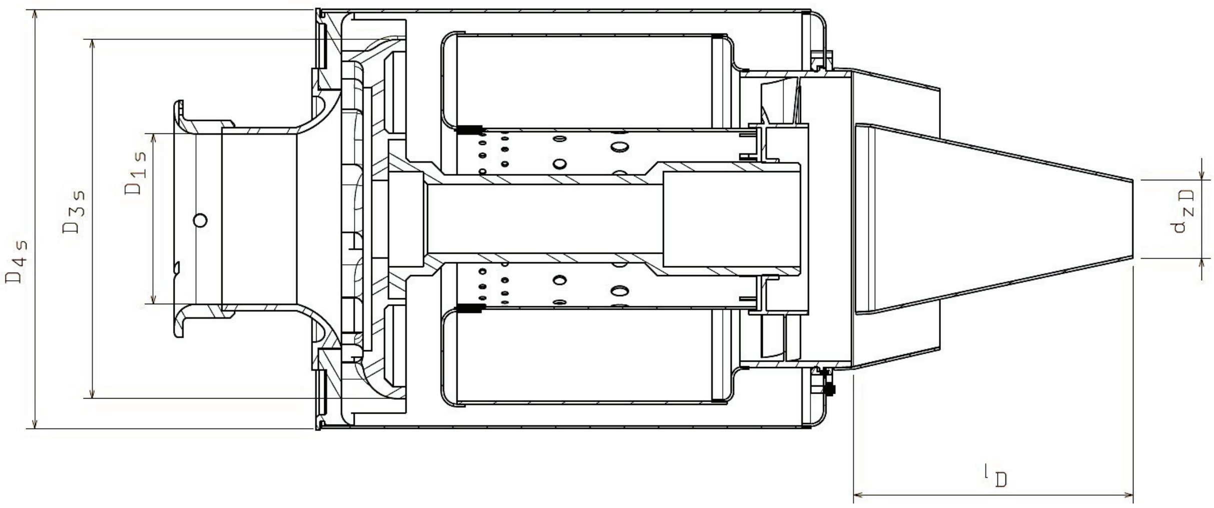

Fig. 3. Basic dimensions of mSO-1 turbojet engine non rotating parts

Weight of the compressor case is described by equation:

$$m_{SPO} = \pi \cdot \rho_D \cdot b_S \cdot \left(10 \cdot b \cdot D_{1S} + \frac{1}{8} \cdot \pi \cdot D_{2S} \cdot (D_{2S} - D_{3S}) + \frac{D_{4S}^2 + D_{2S}^2}{4} \right), \quad (6)$$

where:
D_{1S} – compressor inlet internal dimension (Fig. 3).
Rotor system and rotor housing weight is described by the relationship:

$$m_{OW} = m_{OWO} + m_{OWW}\,. \tag{7}$$

The equation which describes the mass of the rotor housing m_{OWO} to fits any design solutions (with tensioner bearing rotor at the rear and at the front of the shaft) [4, 5]. It was assumed that the mass of the tunnel shaft is about 10% higher the weight of the sleeve which houses the drive shaft (due the assembling elements and contact surfaces).

Mass of engine rotor housing (tunnel shaft) is described by relationship:

$$m_{OWO} = 1.1 \cdot \pi \cdot \rho_D \cdot b_S \cdot l_{OW} \cdot D_{LT}\,, \tag{8}$$

where:
l_{OW} – dimension of shaft tunnel (Fig. 2),
D_{LT} – diameter of turbine bearing (Fig. 2).

Rotor shaft divided into two parts. First corresponds to the distance between the shaft bearings, second to the length that is necessary to embedding the compressor rotor and turbine. Adopted ratio is 60/40 [2]. The design of the rotor shaft is dimensioned by internal bearing diameter D_{WL}. Accepted for technological reasons (the bearing assembly conditions) for the first part of the shaft diameter of $1.4 \cdot D_{WL}$. Dimensions of the second part will be characterized by the equivalent diameter of the shaft equal to $0.6 \cdot D_{WL}$.

$$m_{OWW} = 2.04 \cdot \rho_W \cdot l_{OW} \cdot D_{WL}^2\,, \tag{9}$$

where:
ρ_W – density of an shaft alloy.

Weight of combustor is described by following equation:

$$m_{KS} = g_B \cdot \rho_B \cdot \left[1.17 \cdot \left((D_{4S} - 2 \cdot b)^2 + (D_{LT} + 3 \cdot b)^2 \right) + 2.36 \cdot l_{OW} \cdot (b + D_{LT} + D_{4S}) \right], \tag{10}$$

where:
ρ_B – density of an alloy,
g_B – average wall thickness of alloy sheet.

Presented relationship is true under the assumption that the axial dimension of inner and outer ring is equal to $0.75 \cdot l_{OW}$. The distance of the inner ring from the shaft housing is $3 \cdot b$ (Fig. 2) and the outer ring of the motor housing $2 \cdot b$. The calculations do not take into account the surface of mixing and cooling holes in both rings, as the loss in mass of the rings is completed by welding binder.

Turbine unit weight is described by the relationship:

$$m_{TS} = m_{WTS} + m_{WDTS}\,, \tag{11}$$

The writing order of components in the equation is not accidental because the mass and geometrical dimensions of turbine nozzle is limited by the design of the turbine rotor.

Turbine rotor weight is described by relationship:

$$m_{WTS} = \frac{\pi}{4 \cdot D_Z} \cdot g_{DTS} \cdot \rho_{DTS} \cdot (D_{zt}^2 - D_{WL}^2) \cdot (D_{zt} - h_{DTS})\,, \tag{12}$$

where:
ρ_{DTS} – density of an turbine alloy,
g_{DTS} – average thickness of turbine disk,
h_{DTS} – average blade height of turbine disk.

Mass turbine stator is described by relationship:

$$m_{WDTS} = g_B \cdot \rho_B \cdot \left(1.57 \cdot (D_{zt}^2 - D_{WL}^2) + 25 \cdot g_{DTS} \cdot D_{zt} + 1.2 \cdot g_{DTS} \cdot h_{WDTS} \cdot n_{WDTS} \right), \qquad (13)$$

where:
n_{WDTS} – number of turbine stator blades,
h_{WDTS} – average blade height of turbine stator (nozzle).

The weight of jet pipe is described by following equation:

$$m_{DW} = 1.25 \cdot g_B \cdot \rho_B \cdot \left[\pi \cdot \sqrt{l_D^2 + \left(\frac{D_{zt} - D_{zD}}{2} \right)^2} \cdot (d_{zt} + d_{zD}) \right], \qquad (14)$$

where:
l_D – jet pipe axial dimension,
d_{zD} – jet pipe inner cone exit diameter.

This equation is based on the assumption that the nozzle consists of two truncated cones corresponding to the outer ring and the inner nozzle. Rings weight was increased by 25% due to the connecting ring nozzle to the combustion chamber and internal ribs that fixes position of inner cone [2].

Micro gas turbine outer case is described by relationship:

$$m_{OB} = \pi \cdot g_B \cdot \rho_B \left((D_{4S} - l_{OW}) + 0.25 \cdot (D_{4S}^2 - D_{zt}^2) \right). \qquad (15)$$

Presented equation is true for cylindrical case that is adopted for turbine nozzle assembly.

2. Mass model verification and summary

Numerical model was verified on a prototype design [2]. Real construction weight m_{KONST} was 1.398 kg. Weight of structures calculated on the basis of the present numerical model was 1.371 kg which represents 98% of the real structure. For specific components mass calculation numeric model has a good conformity, considering its simplified nature. The largest percentage share in micro gas turbine design elements had sheet metal structures (outer casing and combustion chamber – Fig. 4). Accordingly, in order to reduce mass of structure designer must adopt sheet metal with smaller thickness also considering the available technologies.

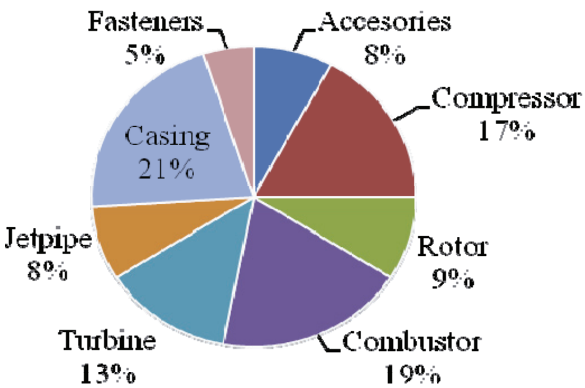

Fig. 4. Micro gas turbine components weights

The computational model was verified also for a representative group of micro turbines (Fig. 5). Observed differences are the result of an alternate to start-up systems by air start or electric motor.

Developed model is a useful tool to optimize the structure mass micro gas turbine jet engine at preliminary study. It also allows to compare the quality of the competitive structure without using reverse engineering or time consuming CAD modelling.

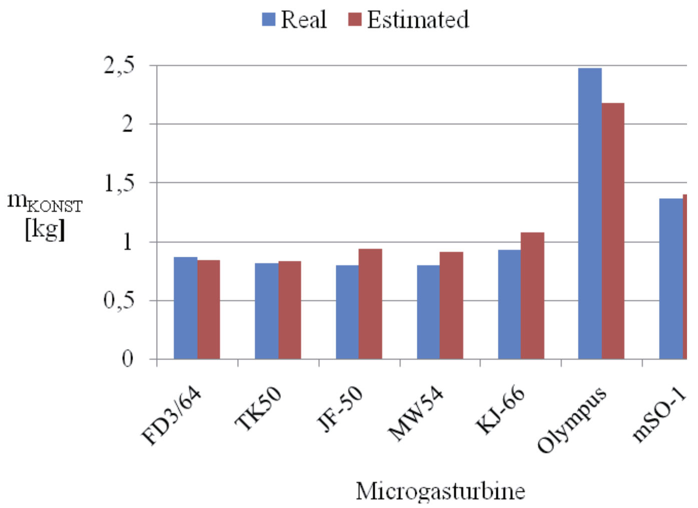

Fig. 5. Comparison of real and estimated weights of several micro gas turbine types

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