Balancing energy processes in turbine engines

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ABSTRACT

The article discusses the issue of balancing energy processes in turbine engines in operation in aeronautic and marine propulsion systems with the aim to analyse and evaluate basic operating parameters. The first part presents the problem of enormous amounts of energy needed for driving fans and compressors of the largest contemporary turbofan engines commonly used in long-distance aviation. The amounts of the transmitted power and the effect of flow parameters and constructional properties of the engines on their performance and real efficiency are evaluated. The second part of the article, devoted to marine applications of turbine engines, presents the energy balance of the kinetic system of torque transmission from main engine turbines to screw propellers in the combined system of COGAG type. The physical model of energy conversion processes executed in this system is presented, along with the physical model of gasodynamic processes taking place in a separate driving turbine of a reversing engine. These models have made the basis for formulating balance equations, which then were used for analysing static and dynamic properties of the analysed type of propulsion, in particular in the aspect of mechanical loss evaluation in its kinematic system.

Keywords: turbine engines, aeronautic and marine propulsion systems, energy balance, mechanical loss

AERONAUTIC PROPULSION SYSTEMS

The need for use of very large thrusts of jet engines in passenger and transport aircraft of increasing take-off weight is a strong motivation for searching for modernisation of turbofan engines, which have been for years used as drives in this aviation branch. The abovementioned modifications aim at further reduction of: fuel consumption, the contents of carbon dioxide and toxins in exhaust gases, and the level of noise emitted during engine operation. These goals are achieved without interfering into the structure of air and exhaust gas flow passages of the engines. Instead, they are oriented on modifying fans, compressors, and turbines, to obtain higher operating efficiency of these components and the engine as a whole. At present, an evolutionary development is being observed in the form of "small steps" consisting in the reduction of flow losses in fans, compressors, and turbines, accompanied by modifications of processes of combustible mixture preparation, reduction of thermal loss in combustion chambers, and, most of all, the increase of the bypass ratio. Development of fans, which in large engines contribute to

over 80% of the generated thrust, is a reason why attempts are made to find constructions of fan rotor units and driving turbines which would enable their cooperation within ranges optimal for both elements.

A tendency is observed to increase engine thrusts. While the initial air-breathing jet engines produced during the Second World War as single-flow turbo jet engines generated thrusts of about 900 daN at air flow rates not exceeding 20 kg/s, the thrusts of turbofan engines presently introduced to operation exceed 33 000 daN, and the air flow rates reach 1300 kg/s. There is no published data on the increase of power needed for driving compressors and, in particular, fans for these types of engines, therefore it seems valuable to assess the power needed for the operation of fans and compressors, and to develop methods to calculate disposable powers of driving turbines.

Figure 1 shows rotor units in arrangements characteristic for "classical" engines with low bypass ratio, and fan constructions of high bypass ratio. In engines used as drives in contemporary combat aircraft units, systems shown in Fig 1a are commonly used. The principle of minimal engine

cross section area was applied in those constructions. The low bypass ratio $\overline{m}$ <1 enables to obtain satisfying moderate fuel consumption, which favourably affects the range of combat missions – at simultaneous reduction of the exhaust gas flow temperature, which makes hitting by enemy's missiles steered towards the heat emission source more difficult.
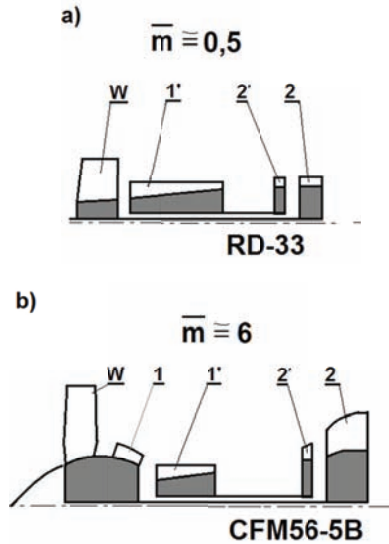

Fig. 1. Comparable sketches of rotor units of air-breathing jet engines: a – low bypass ratio $\overline{m}$, b – moderate bypass ratio: W – fan; 1,1' – low- and high-pressure compressor; 2,2' – low- and high-pressure turbine

For nearly thirty years, turbofan engines have been successfully used in long-distance passenger and transport aviation, first of all due to their low specific fuel consumption. They have replaced the earlier used turbojet engines.

Figure 2 shows sketches of rotor systems of the newest generation of turbofan engines, with very high bypass ratio, which are intended to drive long-distance airplanes with largest take-off weights.
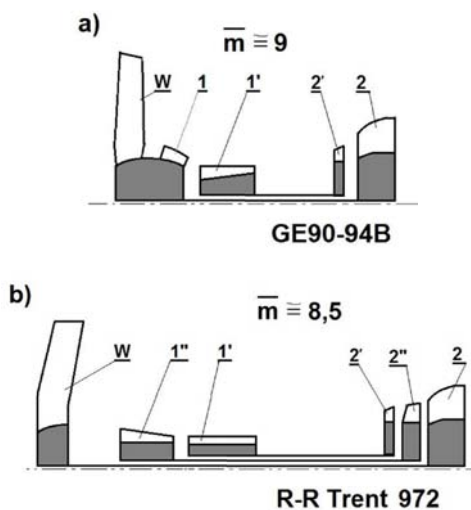

Fig. 2. Sketches of rotor units of turbofan engines with high bypass ratio $\overline{m}$: a – two-rotor engine, b – three-rotor engine. W – fan, 1;1'; - low/ high-pressure compressor, 2;2' – low/high-pressure turbine, 1", 2" – medium-pressure compressor and turbine.

The constructions whose rotor systems are presented above have been designed and introduced to operation by world leading companies: General Electric in the USA, and Rolls-Royce in Europe. The GE engines have two rotors, while those produced by RR have the three-rotor structure. Their performance parameters are comparable with respect to both the obtained thrust and specific fuel consumption at similar air flow rate and bypass ratio.

In order to obtain possibly highest efficiency of the rotor unit, optimal rotational speeds of the compressor and fans should be made as close as possible to the optimal rotational speeds of the driving turbines, hence the need for using multi-rotor units: the high-pressure turbine drives the high-pressure compressor (which usually rotates with higher speed), while the low-pressure turbine is an independent drive for the rotor of the fan, or of the fan and a number of stages of the low-pressure compressor (compare Fig.2 and Fig.3). Favourable results can also be obtained by recovering energy from the exhaust gas and passing it to the fan. The thrust obtained in this way is larger than in the solution with the low bypass ratio engine, in which the energy of the exhaust gas leaving the exhaust nozzle is larger. That is why turbines which drive large diameter fans consist of several stages:
– 4 stages in engine CFM-56 of compression ratio $\pi \cong 25$
– 5 stages in engine Trent of compression ratio $\approx \pi = 35$
– 6 stages in engine GE90 of compression ratio $\approx \pi = 40$
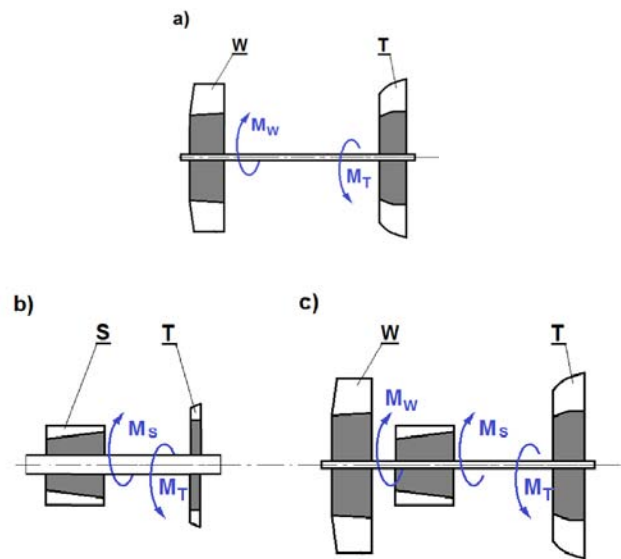

Fig.3. Schemes of torque transmission from turbine (M_T) to fan and compressor: W – fan, S – compressor, T – turbine.

The power needed to drive the fan and compressors, and the disposable power of their turbines can be assessed based on the analysis of relations used for estimating power of these machines. These relations can be found in many specialised manuals (for instance in Polish [1, 2, 3, 5, 7]).

After neglecting friction forces and the power needed for driving electric power generator units (the contributions of which are negligibly small), the balance of the required

power P_n and the disposable power P_T in the rotor, can be presented, depending on the adopted structural arrangement of the rotors (Fig. 3), as:

$$P_n = P_w \ \text{or} \ P_n = P_s \ \text{or} \ P_n = P_w + P_s \qquad (1)$$

but $P_n = P_T$

hence finally:

$$P_T = P_W \qquad (2)$$

or $P_T = P_S$ or $P_T = P_W + P_S$

where particular indices represent: T- turbine, W – fan, S – compressor.

The power required for fan driving can be expressed as:

$$P_w = \dot{m}_w \cdot \frac{k_w}{k_w - 1} \cdot R_w \cdot T_H \cdot \left[(\pi_w)^{\frac{k_w-1}{k_w}} - 1 \right] \cdot \frac{1}{\eta_w} \qquad (3)$$

while the power required for compressor diving is:

$$P_s = \dot{m}_s \cdot \frac{k_s}{k_s - 1} \cdot R_s \cdot T_1 \cdot \left[(\pi_s)^{\frac{k_s-1}{k_s}} - 1 \right] \cdot \frac{1}{\eta_s} \qquad (4)$$

The disposable power of the driving turbine for fan, compressor, or both machines working on a common shaft can be expressed as:

$$P_T = \dot{m}_T \cdot \frac{k_T}{k_T - 1} \cdot R_T \cdot T_T \cdot \left[1 - \left(\frac{1}{\pi_T} \right)^{\frac{k_T-1}{k_T}} \right] \cdot \eta_T \qquad (5)$$

After neglecting the fuel flow rate to the combustion chamber, which is approximately equal to 2% of the mass flow rate of the air flowing through the compressor, the mass flow rates of the air and the exhaust gas in the inner flow duct I and the outer flow duct II of the engine are:

$$\dot{m}_s = \dot{m}_T = \dot{m}_I$$

$$\dot{m}_w = \dot{m}_I + \dot{m}_{II}$$

For preliminary quantitative estimations, powers P_w, P_s and P_T can be calculated using approximate formulas and assuming average values of parameters and coefficients:

$k_s = k_w \approx 1{,}4$ – isentropic exponent for air;
$k_T \approx 1{,}33$ – isentropic exponent for exhaust gas;
$R_s = R_w \approx R_T \approx 28$ [J/kg*K] – individual gas constants for air (R_s and R_w) and exhaust gas (R_T);
$\pi_w \approx 1{,}6$ – average combustion ratio of the fan (assumed by the designer);
$\pi_s = \pi_{SN} \cdot \pi_{SW} = 20 \ldots 50$ – total combustion ratio of the compressor unit, selected by the designer and divided into low- and high-pressure compressor parts;
$\pi_T = p_{wl}/p_{wyl}$ – pressure ratio in the driving turbine - (so called expansion ratio);
$\eta_w = \eta_s \approx 0{,}88$ – average efficiency of fans and compressors (for the take-off range on Earth);
$\eta_T \approx 0{,}91$ – average efficiency of turbines (for the take-off range on Earth);

After taking into account the above assumptions, formulas (3), (4) and (5) are reduced to the following forms:

$$P_w = 1141 \cdot \dot{m}_w \cdot T_H \cdot \left[(\pi_w)^{0,2857} - 1 \right] \qquad (3a)$$

$$P_s = 1141 \cdot m_s \cdot T_1 \cdot \left[(\pi_s)^{0,2857} - 1 \right] \qquad (4a)$$

$$P_T = 1052 \cdot \dot{m}_T \cdot T_T \cdot \left[1 - \left(\frac{1}{\pi_w} \right)^{0,248} \right] \qquad (5a)$$

The air and exhaust gas temperatures in the above formulas refer to inlets to a given rotating machine. The temperature at the fan inlet depends on climatic conditions (ambient temperature T_H) and the speed V and height H of the airplane flight. The same agents affect the air mass flow rate through the fan $\dot{m}_w$ and through the entire engine, which results from changes of air density ρ. Like any rotating machine, the fan generates the volumetric flow, hence for constant V the mass flow rate depends on the density ρ. The following relation is in force:

$$\dot{m}_w = \dot{V}_w \cdot \rho \left(p_H^*, T_H^* \right) \qquad (6)$$

In two-flow turbofan jet engines with high bypass ratio, it is the fan which is the largest receiver of the turbine power. The power required for driving the fan of a large engine (Fig.4) can amount to as much as 70 MW[1] for the take-off range under normal ambient conditions.
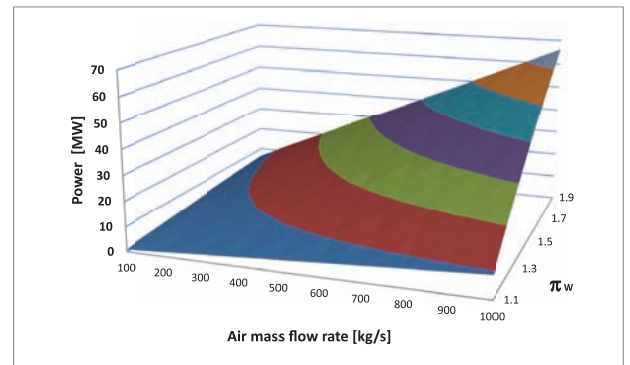

Fig. 4. Power required for fan driving vs. fan compression ratio π_w and air mass flow rate (at temperature of 288K)

Figure 5 shows the relation between the turbine power P_T and the pressure ratio π_T on its stages, for different mass flow rates $\dot{m}_T$ and constant (average) temperature of the exhaust gas at inlet to the analysed rotor unit.

The diagrams are presented to make a quantitative assessment of the effect of main agents on the required power and the disposable power which balance each other in each rotor unit. Their detailed analysis performed for individual engines provides opportunities for selecting thermal and

[1] For comparison : the power of turbogenerators in operation in the Pruszkow power plant is equal to 9MW, in Siedlce: 14,6 MW, and in Zeran: 350 MW

flow parameters which can be reached in the adopted concept of structural arrangement of engine rotors, including the number of turbine stages (and the resultant pressure ratio), and the exhaust gas temperature at the inlet of the turbine which drives the fan.

Flow rates through inner passages of the fan engines are almost twice as large as those in combat aircraft units, at comparable rotational speeds of their rotors.
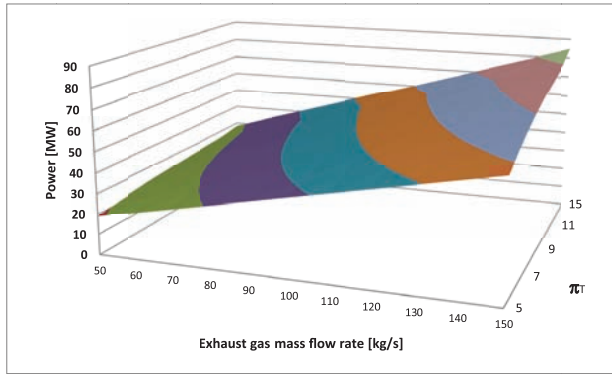

Fig. 5. Disposable power P_T of the turbine for fan driving vs. pressure ratio π_T and exhaust gas mass flow rate

As a result, the required torques in contemporary turbofans are almost twice as large as comparable quantities for combat aircraft units. What is more, due to large values of the required driving power and almost three times as small rotational speed as that of the high-pressure rotors, the torques in the shafts linking the fans with the turbines are larger by as much as thirty times (!). In engines Trent or GE-90 they are of an order of 7000 daNm.

Such large values of the transmitted torque are a serious obstacle in implementation of a concept of engines in which both the fan and its driving turbine would operate at optimal rotational speeds.

A concept of this engine with a reduction gear is shown in Fig.6. Both the fan and the driving turbine operate at rotational speeds which are optimal for them. An engine with this structure, so called GTF (Geared Turbo Fan), and the reduction gear of the transmission ratio of about 3:1 was certified in 2013.
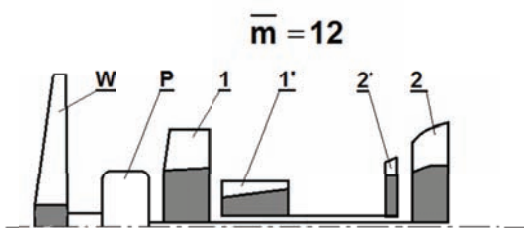

Fig. 6. Scheme of rotor units of P&W 1124G engine of GTF type with fan driven via reduction gear: W- fan, P – reduction gear; 1,1' – low- and high-pressure compressors, 2 – turbine for driving fan and low-pressure compressor, 2' – turbine for driving high-pressure compressor.

This engine, labelled as PW 1519/21/24G and generating the thrust of (85kN ÷ 107kN), is intended to drive airplanes Bombardier C100 and C300 which are expected to come into operation in 2015.

It is likely, however, that large values of torques transmitted in engines with thrusts exceeding 300 kN, which are in use in large passenger and transport airplanes, will force the use of large and heavy transmission gears, all this postponing the time of appearance of driving systems of this type.

MARINE PROPULSION SYSTEMS

A totally different situation has place in marine applications of turbine engines, where transmission systems which are sometimes very extended[2] and transmit torques of an order of MNm's make the basis for marine propulsion systems. Sample structural solutions of this type of systems are shown in Fig. 7.
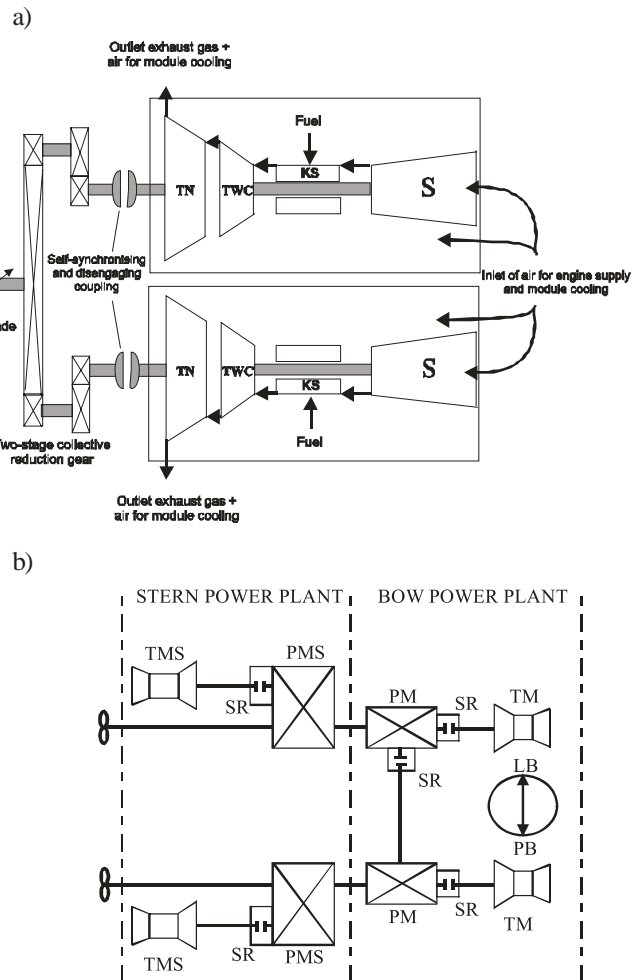
a)

b)

Fig. 7. Schematic diagrams of propulsion systems with turbine engines uniform system with two engines LM2500 made by General Electric, b) combined system COGAG (Combined Gas turbine and Gas Turbine) with ZORYA engines: continuous power engine TM of UGT3000 type, and peak power engine TMS of UGT6000 type. TN, TWC – respectively: separate driving turbine and high-pressure turbine, S – compressor, PM, PMS – respectively: continuous and peak operation reduction gear, SR – disengaging coupling, LB, PB – respectively: port side and starboard side.

[2] Driving systems for hovercrafts with turbine engines can have even nine reduction gears [http://www.zorya.com.ua].

While in aircraft drives the problem of application of reduction gears mainly refers to remarkable increase of the net weight of the aircraft, in marine propulsion systems, especially in combined options, attention is focused on increasing total mechanical losses which decrease basic parameters of the dynamics of navigation.

The energy balance of the turbine engine should be analysed only in combination with the power receiver. In marine application this receiver is the mechanical system of torque transmission and conversion from the main engine to the propeller screw (or simultaneously to a number of screws) cooperating with the ship hull, or the so-called locomotive system. The structure of flow of energy fluxes in the entire locomotive system makes its own individual property resulting from the use of the structural form and algorithms executed in the automatic control system of propulsion engine load. In unsteady operating conditions each subsystem of the locomotive system of the ship reveals specific abilities to accumulate (and dissipate) different forms of energy and substances, which are decisive for the dynamics of the executed energy conversion processes. This issue is of utmost importance for locomotive systems of warships, which are characteristic for changing power demand and can spend even as much as 90% of the total time for navigating at cruising or minimal speeds. On the other hand, at any time they should be able to develop immediately much higher speeds, up to the maximal speed, to perform military action or to avoid collision.

The starting point for balancing the energy of the marine turbine engine is developing a physical model of energy conversion processes executed by the locomotive system. A sample model of this type is shown in Fig. 8. Here, a number of functional modules are named, which are to be analysed in causal aspect. For each module, input and output parameters being the variables of the energy state of the system were determined.

The description of analytical processes, prepared based on the equations of unsteady balance of energy and substance for particular functional modules, should take into account a number of simplifying assumptions which determine the level of specificity of the developed mathematical model [Korczewski, 1999]. Limiting our attention only to the kinematic system of torque transmission from the main engine turbines to the screw propellers, consisting of two propulsion units, one for the port side and one for the starboard side, connected with each other by the transverse shaft, it was assumed that:

- the analysed ship navigates only along a straight line, parallel to the undisturbed sea surface, at unchanged weight of displacement,
- the water region of navigation is sufficiently wide and deep, the motion of the ship is always obtained using two propulsion units and the operation of the both units is identical,
- energy conversion processes executed in particular functional modules of the system are described using
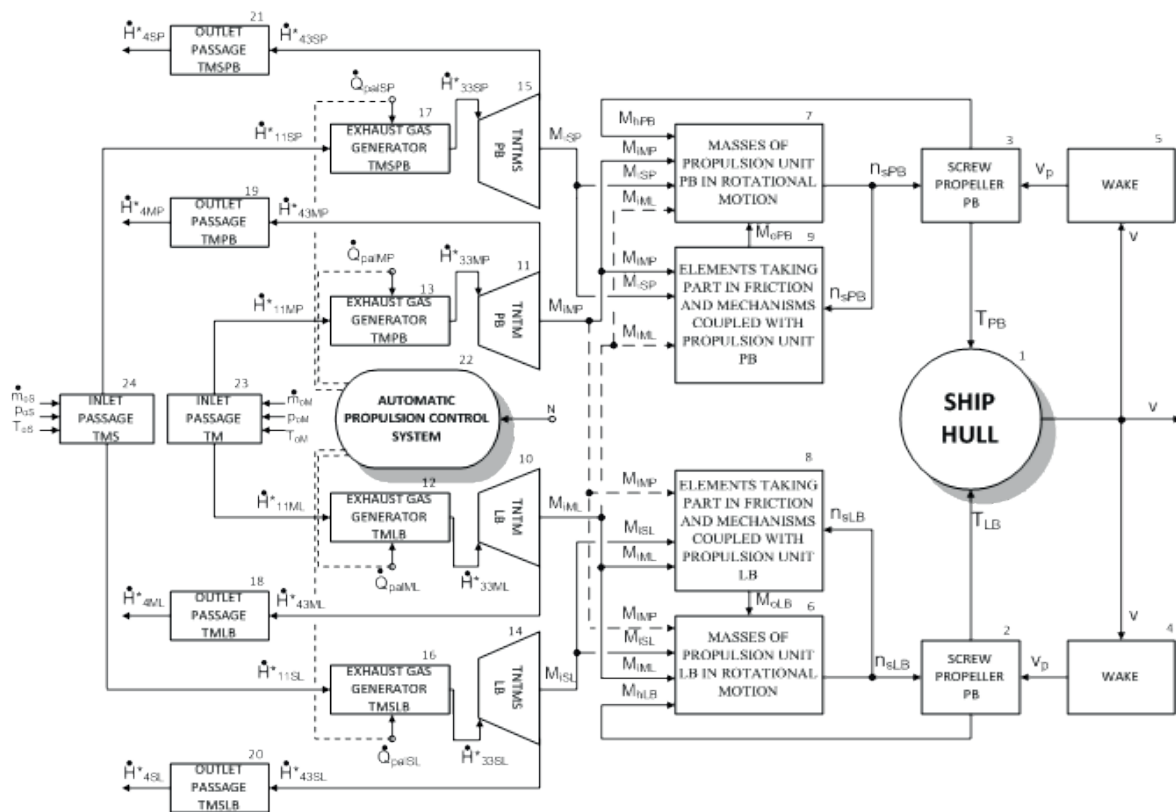

Fig. 8. Physical model of the locomotive system of the ship with COGAG propulsion system. $\dot{H}$ - enthalpy flux, $\dot{Q}$ - heat flux, M – torque, T – propeller thrust, v – ship navigation speed, v_p – speed of advance of screw propeller with respect to the surrounding water, n – rotational speed, $\dot{m}$ - mass flow rate, N – angular position of engine control lever.

models with concentrated parameters having the form of first-order ordinary differential equations.

- delays resulting from the dynamics of operation of the automatic system for engine fuel supply and propulsion load control are neglected, treating the system as the inertialess element,
- bearings of the kinematic system of torque transmission are ideally rigid – the only possible motion is the rotational motion with respect to the axis of the bearing.

With these simplifications, the dynamics of operation of the mechanical system of one of two identical propulsion systems is described by the following equations:

a) equation of rotational motion of the propulsion system shafting:

$$\frac{dn_{sLB}}{d\tau} = \frac{1}{2\pi I_z} \cdot (M_{iML} + M_{iSL} + M_{iMP} - M_{hLB} - M_{oLB})$$

(7)

where: I_z – polar moment of inertia of masses in the rotational motion of one propulsion unit from the rotor system of a separate propulsion turbine of each operating engine to the screw propeller, reduced to the propulsion shaft axis.

b) equation of mechanical load of the propulsion unit:

$$M_{oLB} = M_{mTN} + M_{mPMLB} + M_{mPMSLB} + M_{mWP} + M_{msLB}$$

(8)

where: M_{mTN} – total moment of mechanical losses of the coupled rotor systems of separate propulsion turbines of each engine working for the unit:

$$M_{mTN} = M_{mTNML} + M_{mTNSL} + M_{mTNMP}$$ (9)

Pressure in line shafting bearings of a separate propulsion turbine depend on the transmitted torque and rotational speed. At this assumption the anti-torque generated by friction is:

$$M_{mTNML} = f(M_{iML}, n_{TNML})$$ (10)

After linearising Equation (10), e.g. expanding it into Taylor series and omitting higher-order terms as negligible small, we get:

$$M_{mTNML} = M_{mTNMLo} + \left(\frac{\partial M_{mTNML}}{\partial M_{iML}}\right) \cdot (M_{iML} - M_{iMLo}) +$$

$$+ \left(\frac{\partial M_{mTNML}}{\partial n_{TNML}}\right) \cdot (n_{TNML} - n_{TNMLo})$$

(11)

where: M_{mPMLB} - moment of mechanical losses of the continuous operation reduction gear.

Forces acting in the bearings and on inter-tooth pressure surfaces of the gear depend on the rotational speed and the torque which loads the gear. At this assumption the anti-torque generated by friction is:

$$M_{mPMLB} = f(M_{iML}, n_{TNML}, \eta_{mTNML})$$ (12)

After linearising Equation (12) we get:

$$M_{mPMLB} = M_{mPMLBo} + \left(\frac{\partial M_{mPMLB}}{\partial M_{iML}}\right) \cdot (M_{iML} - M_{iMLo}) +$$

$$+ \left(\frac{\partial M_{mPMLB}}{\partial n_{TNML}}\right) \cdot (n_{TNML} - n_{TNMLo}) +$$

$$+ \left(\frac{\partial M_{mPMLB}}{\partial \eta_{mTNML}}\right) \cdot (\eta_{mTNML} - \eta_{mTNMLo})$$

(13)

where: M_{mPMSLB} - moment of mechanical loss of peak operation reduction gear, at the same assumptions as for the continuous operation gear:

$$M_{mPMSLB} = f(M_{iML}, n_{TNML}, \eta_{mTNML}, i_{PM}, \eta_{mPMLB}, M_{iSL}, n_{TNSL}, \eta_{mTNSL})$$ (14)

After linearising Equation (14) we get:

$$M_{mPMSLB} = M_{mPMSLBo} + \left(\frac{\partial M_{mPMSLB}}{\partial M_{iML}}\right) \cdot (M_{iML} - M_{iMLo}) + \left(\frac{\partial M_{mPMSLB}}{\partial n_{TNML}}\right) \cdot (n_{TNML} -$$

$$- n_{TNMLo}) + \left(\frac{\partial M_{mPMSLB}}{\partial \eta_{mTNML}}\right) \cdot (\eta_{mTNML} - \eta_{mTNMLo)} + \left(\frac{\partial M_{mPMSLB}}{\partial \eta_{mPMLB}}\right) \cdot (\eta_{mPMLB} -$$

$$- \eta_{mPMLBo}) + \left(\frac{\partial M_{mPMSLB}}{\partial M_{iSL}}\right) \cdot (M_{iSL} - M_{iSLo}) + \left(\frac{\partial M_{mPMSLB}}{\partial n_{TNSL}}\right) \cdot (n_{TNSL} - n_{TNSLo}) +$$

$$+ \left(\frac{\partial M_{mPMSLB}}{\partial \eta_{TNSL}}\right) \cdot (\eta_{TNSL} - \eta_{TNSLo})$$

(15)

where: M_{mWP} - moment of mechanical loss of the transverse shaft.

The transverse shaft friction moment depends on the rotational speed and the transmitted load:

$$M_{mWP} = f(M_{iML}, n_{TNML}, \eta_{mTNML}, i_{PKPM}, \eta_{mPKPM}, M_{iMP}, n_{TNMP}, \eta_{mTNMP})$$

(16)

where: i_{PKPM}, η_{mPKPM} – represent, respectively: transmission ratio and mechanical efficiency of the angular transmission stage of the transverse shaft of the continuous operation reduction gear.

After linearising Equation (16) we get:

$$M_{mWP} = M_{mWPo} + \left(\frac{\partial M_{mWP}}{\partial M_{iML}}\right) \cdot (M_{iML} - M_{iMLo}) + \left(\frac{\partial M_{mWP}}{\partial n_{TNML}}\right) \cdot (n_{TNML} - n_{TNMLo}) +$$

$$+ \left(\frac{\partial M_{mWP}}{\partial \eta_{mTNML}}\right) \cdot (\eta_{mTNML} - \eta_{mTNMLo}) + \left(\frac{\partial M_{mWP}}{\partial \eta_{mPKPM}}\right) \cdot (\eta_{mPKPM} - \eta_{mPKPMo}) +$$

$$+ \left(\frac{\partial M_{mWP}}{\partial M_{iMP}}\right) \cdot (M_{iMP} - M_{iMPo}) + \left(\frac{\partial M_{mWP}}{\partial n_{TNMP}}\right) \cdot (n_{TNMP} - n_{TNMPo}) +$$

$$+ \left(\frac{\partial M_{mWP}}{\partial \eta_{mTNMP}}\right) \cdot (\eta_{mTNMP} - \eta_{mTNMPo})$$

(17)

where: M_{msLB} – total moment of mechanical losses of the propeller shaft. The friction moment of the propeller shaft depends on the torque and rotational speed:

$$M_{msLB} = f(M_{iML}, n_{TNML}, \eta_{mTNML}, i_{PM}, \eta_{mPMLB}, M_{iSL}, n_{TNSL}, \eta_{mTNSL}, i_{PMS}, \eta_{mPMSLB}, n_{sLB})$$

(18)

After linearising Equation (18) we get:

$$M_{msLB} = M_{msLBo} + \left(\frac{\partial M_{msLB}}{\partial M_{iML}}\right) \cdot (M_{iML} - M_{iMLo}) + \left(\frac{\partial M_{msLB}}{\partial n_{TNML}}\right) \cdot (n_{TNML} - n_{TNMLo}) +$$

$$+ \left(\frac{\partial M_{msLB}}{\partial \eta_{mTNML}}\right) \cdot (\eta_{mTNML} - \eta_{mTNMLo)}) + \left(\frac{\partial M_{msLB}}{\partial \eta_{mPMLB}}\right) \cdot (\eta_{mPMLB} - \eta_{mPMLBo}) + \left(\frac{\partial M_{msLB}}{\partial M_{iSL}}\right) \cdot$$

$$(M_{iSL} - M_{iSLo}) + \left(\frac{\partial M_{msLB}}{\partial n_{TNSL}}\right) \cdot (n_{TNSL} - n_{TNSLo}) + \left(\frac{\partial M_{msLB}}{\partial \eta_{TNSL}}\right) \cdot (\eta_{TNSL} - \eta_{RNSLo}) +$$

$$+ \left(\frac{\partial M_{msLB}}{\partial \eta_{mPMSLB}}\right) \cdot (\eta_{mPMSLB} - \eta_{mPMSLBo}) + \left(\frac{\partial M_{msLB}}{\partial n_{sLB}}\right) \cdot (n_{sLB} - n_{sLBo})$$

(19)

Partial derivatives in the linearised initial equations describing friction processes in the analysed unit of the kinematic torque transmission system are calculated based on the characteristics of the line shafting and the reduction gears, delivered by the producer.

Since the mechanical losses in: the rotor units of the separate propulsion turbines, the line shafting, and the reduction gears of the analysed propulsion system, do not exceed, respectively: 0.5%, 0.8% and 2% at nominal load, an acceptable assumption is that the pressure forces acing in the bearings and on inter-tooth pressure surfaces do not depend on torques transmitted by the line shafting. Their values are approximately constant (possible changes may only result from longitudinal hull deformations, caused by waves, for instance). Consequently, in the first stage of balancing energy conversion in the turbine propulsion system an assumption was made that the total torque (load) in rotational motion of the propulsion unit which is needed to overcome friction forces in: line shafting bearings, connections of toothed elements of the reduction gears, and other mechanisms coupled with them, is proportional to the square of the rotational speed of the propulsion shaft:

$$M_{oLB} = M_{oLB(nom)} \cdot \left(\frac{n_{sLB}}{n_{sLB(nom)}}\right)^2$$

(20)

The exhaust gas generator of each propulsion engine cooperates with a kinematically independent reversible propulsion turbine, which allows the direction of ship motion to be reversed: AHEAD/ASTERN – Fig. 9. Controlling the direction of the exhaust gas flow through the lower or upper cascade of rotor blades is executed by simultaneous rotation of stator blades 1 and lifting the exhaust gas bleed band 5. The blades for "Motion ASTERN", the number of which is about twice as big as that of the blades for "Motion AHEAD", have inversed profiles and are separated by the shelf 3 from the lower "Motion AHEAD" cascade. Simultaneous partial opening of both flow passages produces an effect which balances gasodynamic moments in the propulsion turbine rotor, thus ensuring smooth ship manoeuvring. The maximal engine power at the propulsion turbine in the "Motion ASTERN" mode is approximately equal to 10% of the power in the "Motion AHEAD" mode. The time of turbine reversing and changing the direction of motion from AHEAD to ASTERN (and vice versa) is equal to 4÷7 seconds.

The physical model of energy conversion processes executed in a separate propulsion turbine with the exhaust gas outlet passage is given in Fig. 10.
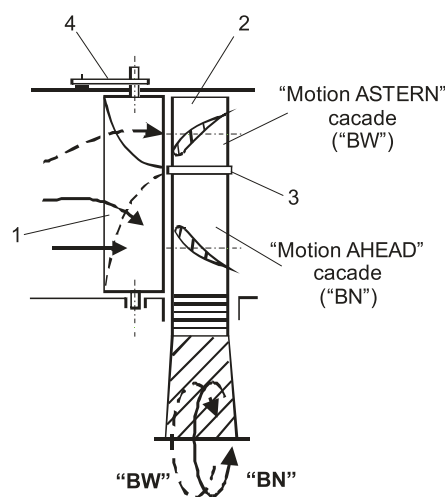

Fig. 9. Scheme of reversal propulsion turbine. 1- adjustable stator, 2 – two-storey rotor blade cascade, 3 – shelf, 4 – mechanism which rotates adjustable stator, 5 – bleed band.
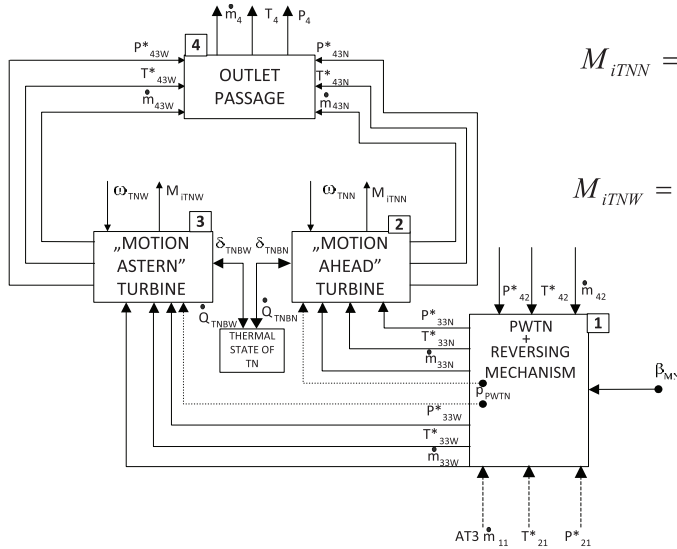
Fig. 10. Physical model of energy conversion processes executed in reversible propulsion turbine with the exhaust gas outlet passage PWTN – space between exhaust gas generator and propulsion turbine, M – torque, ϖ – angular speed, p*, T* – total pressure and temperature, respectively, $\dot{m}$ - mass flow rate, AT3 – mass contribution of air for cooling the reversing mechanism of the turbine, δ- tip clearance, β - setting angle of engine reverse mechanism.

Mutual gasodynamic connection exists between the propulsion turbine and the engine exhaust gas generator. The dynamics of the mutual interaction is controlled by accumulative properties of the kinematic system of the propulsion unit, and the potential for energy and substance accumulation in the broad gas spaces of the exhaust gas outlet passage and the passage linking the exhaust gas generator with the propulsion turbine. As a consequence of the gasodynamic interaction of the gas spaces, which depends on the nature of the executed unsteady process, the kinetic energy of the heavy ship propeller line can be either diffused or cumulated.

In the physical model of the propulsion turbine the following dynamic elements were named:

– gas space between exhaust gas generator and propulsion turbine - 1,
– propulsion turbine for "Motion AHEAD" - 2,
– propulsion turbine for "Motion ASTERN" - 3,
– exhaust gas outlet passage - 4.

The internal (gasodynamic) moment of the propulsion turbine is given by the equation:

– for motion "AHEAD":

$$M_{iTNN} = \frac{1}{\omega_{TNN}} \cdot \left(\dot{H}^*_{33N} - \dot{H}^*_{43N} \right) \qquad (21)$$

– for motion " ASTERN":

$$M_{iTNW} = \frac{1}{\omega_{TNW}} \cdot \left(\dot{H}^*_{33W} - \dot{H}^*_{43W} \right) \qquad (22)$$

After expanding Equations (21) and (22), the internal moment of the propulsion turbine can be expressed, depending on gasodynamic parameters, as:

$$M_{iTNN} = \frac{1}{\omega_{TNN}} \cdot \left[\dot{m}_{33N} \cdot c_{pspTNN} \cdot T^*_{33N} \cdot \left(1 - \varepsilon^{*\,-m_{TNN}}_{TNN} \right) \cdot \eta^*_{eTNN} \right]$$

(23)

$$M_{iTNW} = \frac{1}{\omega_{TNW}} \cdot \left[\left(\dot{m}_{33W} \cdot c_{pspTNW} \cdot T^*_{33W} \cdot \left(1 - \varepsilon^{*\,-m_{TNW}}_{TNW} \right) \cdot \eta^*_{eTNW} \right] \right.$$

(24)

where:

$\eta^*_{eTNN}, \eta^*_{eTNW}$ - efficiencies of the process of working medium expansion in the propulsion turbine for, respectively, the motion AHEAD and the motion ASTERN,

c_{pspTNN}, c_{pspTNW} - average specific heats at constant pressure of the real exhaust gas within the range of the process of isentropic expansion of the working medium in the propulsion turbine for, respectively, the motion AHEAD and the motion ASTERN,

$\varepsilon^*_{TNN}, \varepsilon^*_{TNW}$ - pressure ratio in the propulsion turbine for, respectively, the motion AHEAD and the motion ASTERN,

m_{TNN}, m_{TNW} - default exponent, equal to $\chi - 1/\chi$ for temperature ranges of isentropic processes in the propulsion turbine for, respectively, the motion AHEAD and the motion ASTERN.

FINAL REMARKS AND CONCLUSIONS

Heavy loads transmitted by shafts which connect jet engine fans with the driving turbines can be a source of their damage leading to the failure of the entire engine and, frequently, to the plane crash. A list of examples of such events includes:

- crash of the plane IŁ-62 "Kopernik" PLL-LOT on March 14, 1980, the reason for which was twisting apart of the shaft connecting the low-pressure turbine with the fan of the engine NK-8, due to material fatigue in the area where a notch resulting from incorrect machining was situated [6];

- crash of the plane IŁ-62 "Kościuszko" PLL-LOT on May 9, 1987, the reason of which was also twisting apart of the shaft connecting the low-pressure turbine with the fan of the engine D-30 KU. This crash was an effect of the following chain of events: firstly, an excessive clearance appeared as a result of wear of rollers in the seized bearing situated between the low-pressure and high-pressure rotor shafts, then the labyrinth seal on one shaft started rubbing against the second shaft, and the resultant heat emitted in this friction process was so large that it increased the temperature of the material in this cross section to the level which drastically reduced its strength;

- failure of the engine R-R Trent 900 on the plane Airbus 380 owned by Quantas on November 4, 2010. Here, twisting apart of the shaft connecting the turbine with the compressor has led to the explosion of the medium stage turbine; earlier the shaft had been overheated

because of local fire caused by oil leak from a broken pipe situated close to the combustion chamber.

For a long time, control system designers have been familiar with the problem of reduction of the maximal torque transmitted by turbine jet rotors. In propeller engines and helicopter engines, special elements are installed, most often in reduction gears, which enable direct measurement of this torque. Control systems of these engines are equipped with limiters which reduce the flow of fuel to the combustion chamber when permissible torque values are exceeded. In jet engines, in which the measurement of the torque which twists the shaft is not possible, an intermediate solution is most often used which consists in limiting the maximal flow of fuel to the combustion chamber, i.e. limiting the maximal power of the engine turbine. The introduction of this limit is useful when the air pressure at engine inlet reaches maximal values (for instance, plane flight with maximal speed at low altitude in winter conditions). In some engines systems are also used which cut off rapidly the fuel flow to the combustion chamber when the "link" between the turbine and compressor, or fan, is "lost".

Improving numerical models describing the above analysed issue is well justified by the fact that natural-scale testing of contemporary constructions of turbines and fans of large engines is troublesome, due to demand for extremely high powers. As a consequence, tests are performed on smaller-scale models of these units, or alternatively, at the design examination stage the fan of an existing engine is replaced by a new, prototype version, with simultaneous making use of the known characteristics of the already used compressor, combustion chamber, and turbine.

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