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Heat transfer and lubrication of turboshaft motor-reducer

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Abstract. Turboshaft engines, as the rule, contains gear transmission unit – reducer and belong to the group of drive systems with the name motor-reducer. These are the compact and autonomous assemblies for various applications. In the case of turboshaft engine in combination with high speed reducer, arise the set of phenomenon which has to be solved. Majority of them are in relation to reducer protection of overheating and of gears and bearings failures. The article contains analysis of heat sources, heat transfer through design structure and heat taking out in order to maintain acceptable temperature level of reducer lubricant. Theoretical discussions are supported with various experimental results and testing procedures, including analytic calculations. The set of design solutions for reducer protection when reducer located in the area of hot gas flow, is the main content. The case study is innovative design of turboshaft motor-reducer with free turbine which provides flexible operation and compact design structure.

1. Introduction

Turbo structures have the main function to drive turbo compressor in order to provide air under the pressure for fuel combustion. The gas of combustion drives turbine for compressor rotor traction. This part of structure present by itself gas generator which can has various applications. Produced gas by flow through the nozzle can produce jet force – turbojet engine. In this solution the turbine power is equal to power of air compressor. In the next application the compressor and turbine shaft can be coupled to some rotating operating organ, by using transmission unit or directly without gearbox. This structure presents turboshaft engine where turbine directly connected to operating part of structure. The power of turbine has to provide traction of air compressor together with operating part of structure. For flexible operation, the gas-generator produces the gas flow which drives additional free turbine connected to operating rotating system together with gear transmission unit – reducer. In Figure 1 this solutions are presented. Figure. 1a shows the gas generator which can be turbojet engine or turboshaft engine with reducer.

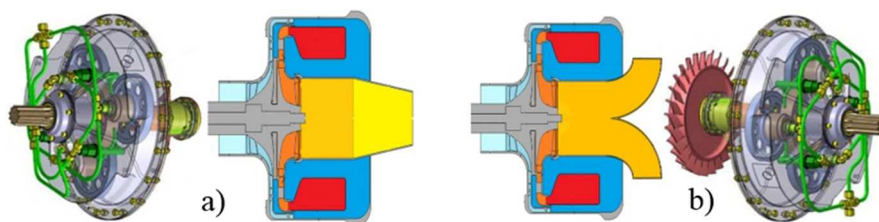


Figure 1. Motor-reducer relations: a) direct coupled reducer at cold side and b) free turbine connection at the hot side of gas generator.

Figure 1b shows relation of the gas generator with free turbine and reducer. In the area of turbo-shaft engines (motor-reducer combination) dominates design solutions where reducer directly connected to compressor-turbine shaft and located at the cold side of the gas generator. This position is significantly better for reducer because is protected of outside heating. Some existing solutions with free turbine (Figure 1b) are without reducer or with reducer located at the higher distance from the hot gas flow. The free turbine solutions are with various advantages in exploitation but exist a very few compact solutions at the market. Specific compact design solution is developed by the authors participation and presents the subject of analysis in this work.

Operation properties of turbo engines is the subject of various works in various articles and with various objectives. Turbojet engine of small scale is the subject in [1] with the objective to find possibility for consumption of alternative fuel. Turboshaft engines is the subject of various effects analysis such as the noise effect [2] and other effects or properties. The objective of this article is presentation and analysis of inside and outside heat sources of reducers in assembly to turboshaft engine with free turbine of specific design. The design is carried out to be maximally compact. Compactness is provided also in the gas generator design, reducer design and also in the joint of gas generator and reducer. The objective is to present the set of design solutions which provides possibility to prevent heat transfer from free turbine area into reducer and to take out the heat from reducer. Maintenance of lubrication oil temperature of necessary level provides prolongation service life of reducer components and overall service life of reducer or caring capacity of reducer.

2. Inside heating and heat transfer

Resistances in the gear connections and in the bearings transform the part of mechanical energy in the heat. Experimental and analytic research of these transformations in the gear transmission units are taken out through the many years in the past. The results show that about 1.5% of transmitted power transforms in the heat per one gear mesh together with bearings. For the gearbox with the two steps of transmission, such as our case for analysis, this are 3%, and for the power of 170 kW, inside heat in gearbox is 5.1kW. This heat has to be transmitted into surrounding through the walls. Increase of gear transmission unit compatibility reduces gearbox surface and quantity of the heat which can be radiated into surrounding. Extreme high speed of rotation increases reduction of dimensions and radiation of heat. This is the reason that inside heat of these kinds of reducers have to be taken out by additional cooling system.

Correct gear operation needs forming of oil film between gear flanks without direct contact of the flanks (Figure 2a). Oil film provides the contact pressure and the stress distribution which correspond to the pitting failure. Without oil film under the high pressure and extreme high speed increase local temperature in the contacts and pitting transform into the scoring with teeth overheating and progressive wear. Extreme high speed of rotation produces extreme centrifugal forces which acting at the oil and remove oil film [3]. In order to prevent it, oil under the pressure spraying from the both sides of teeth connection (Figure 2a).

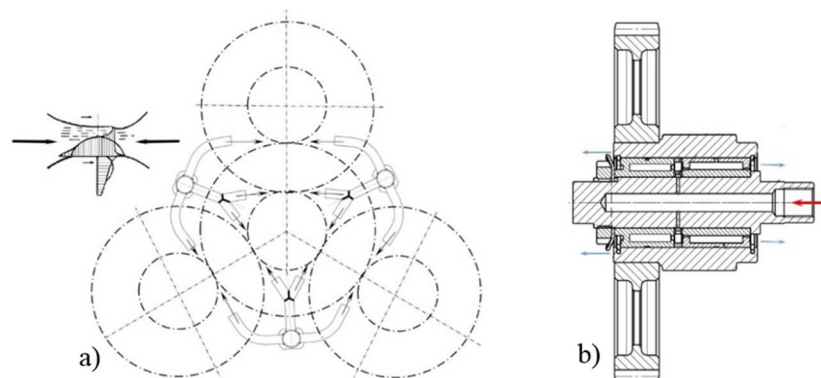


Figure 2. Cooling and lubrication of (a) gears and (b) bearings.

Lubrication of bearings with extreme high speed of rotation is also specific. The oil has to be injected directly in the bearings. In Figure 2b is presented the oil direction which under the pressure comes through stable axes to the bearings. The big quantity of oil can increase bearing resistance, but for the heat taking out, fluid flow is required. For this purposes, the oil fog is suitable. The bearings of input shaft and bearings of the three parallel branches of transmission, lubricates and heat taking out, oil fog which is result of mixing of the oil and air under the pressure.

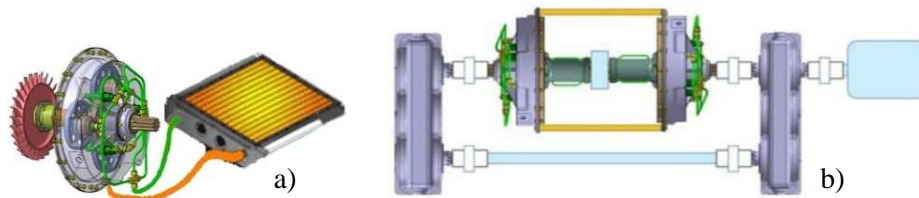


Figure 3. Cooling of reducer (a) and reducer testing (b).

In order to maintain the oil temperature at the acceptable level, it is necessary to cool of oil. For this purpose the reducer is equipped by the system of oil circulation driven by the gear pump together with filter and oil cooler (Figure 3a). The quantity of oil flow corresponds to the oil heat characteristic $c=1.8 \cdot 10^3 \text{ J/(kgK)}$ and to temperature difference of oil output and input in reducer $\Delta\vartheta=30^{\circ}$. In order to take out calculated heat of 5.1 kW, oil flow of $m = Q / (c\Delta\vartheta) = 5.1 \cdot 10^3 / (1.8 \cdot 10^3 \cdot 30) = 0.0944 \text{ kg/s}$, is necessary. For oil density of 0.9kg/l, volume flow is 6.3 liters per minute. This is calculated quantity of oil flow, but this is data for orientation only. It is not possible to know that oil cooler can make temperature difference $\Delta\vartheta=30^{\circ}$. One part of heat quantity will be radiated from gearbox surface in surrounding in dependence of temperature difference between surface and air in surrounding. In order to establish equilibrium between quantity of produced heat inside of gearbox and heat taken out, together with temperature of oil in gearbox about 90°C , it is necessary to arrange systematic laboratory testing. In Figure 3b is presented testing rig based on power circulation principle. The two gearboxes for testing are back-to-back connected and placed in the close system of power circulation. By elastic deformation of entire system using necessary testing torque, before the test, the system is pre-stressed by this torque. When rotation start, the system operates with the power which corresponds to applied torque and speed of rotation. Cooling and lubrication system operates approximately at the same way independently of the gearbox load. By variation of load it is possible to identify gearbox load where is established equilibrium between produced heat and the heat taken out and necessary oil temperature inside of gearbox.

3. Outside heating of gearbox

Gearbox of turboshaft engine is located at the hot side of the gas generator (Figure 1b). The gas flow drives free turbine and gear transmission unit. The high speed of rotation of free turbine, for example 40000 rpm transforms into 6000 rpm at output shaft. The gas of cc 630°C drives free turbine blades and heats them. Gas continue to flow through radial outputs and also heats the walls of turbine housing. Researches presented in [4-6] and many of others shows that temperature of blades and the walls are similar to the gas temperature. Close located gearbox to the gas flow and directly connected to turbine housing, can to be overheated together with inside oil for the gears and bearings lubrication. Tracings of the heat coming inside of the gearbox are presented in the Figure 4. The main tracing (1) is conduction of the input shaft. The shaft is directly connected to the free turbine exposed to high temperature. At the other end of the shaft is located input gear inside of gearbox. This gear presents significant source of the heat in gearbox. The other tracing (2) is gearbox inside wall i.e. bulkhead between engine and reducer. This wall (still plate with ribs) is exposed to heating by the three ways marked in Figure 4 with (a), (b) and (c). The first way (a) is direct contact metal-to-metal with worm components of engine, such as turbine housing and bearing carrier of free turbine and input shaft. The

second way (b) is the heat radiation from the surface of flow channel into the inside space and bulkhead and turbine carrier. This radiation can significantly increase the temperature of mentioned parts. The thread way (3) is direct input of combustion gases through the clearance between turbine and housing. Flow of worm gas in the closed space behind the gearbox wall can be effective for significant heating of reducer oil. Tracing (3) of the heat transmission Figure 4 is heating of outside walls of gearbox. This is the component in direct contact to bulkhead plate between engine and reducer. Heat conduction from bulkhead increase temperature of the outside walls. Also exhausted gases into surrounding increase temperature of surrounding air and also temperature of outside walls.

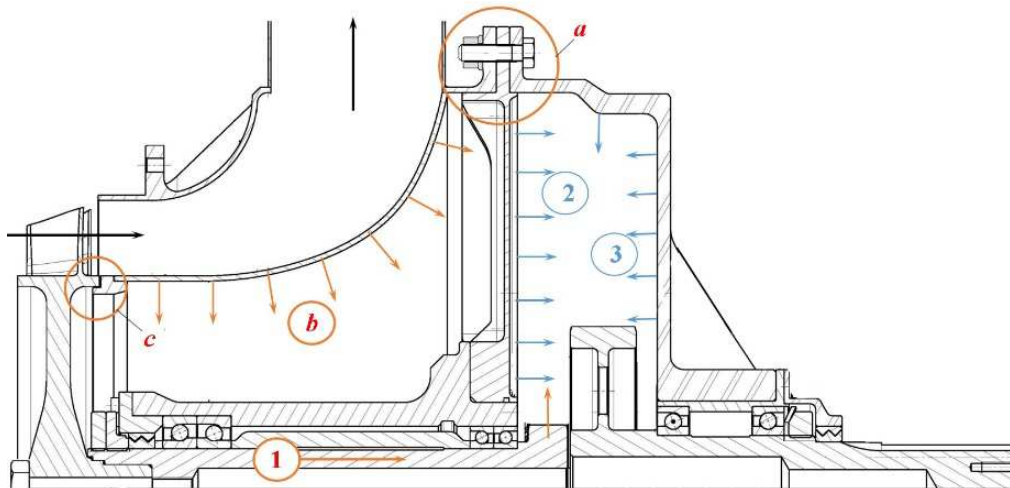


Figure 4. Tracings and ways of the heat transmission.

4. Design solutions for gearbox isolation

Previous analysis shows that outside heating of reducers installed close to free turbine can be significant. Extensive and systematic testing can offer the answer about the quantity of the heat which get in the gearbox. It is necessary to expect that value of outside heat can be much higher in comparison to inside heat. The system for lubrication and cooling can be overloaded and can't to take out overall heat quantity and maintain necessary temperature level inside of gearbox. Prevention against outside heating and reduction of outside heat which can come in the gearbox, it is possible to provide by the set of design actions. This is the set of design solutions oriented to reduction of heat conduction and heat radiation from the hot side of design structure.

4.1. Isolation against heat conduction and radiation

Direct contact metal-to-metal between engine and reducer structure exist in the connection flange, marked in Figure 4 by the letter (a). Possible design solution is application of nonmetal isolation insert between the flanges and nonmetal cylindrical capsule and washers for the screw bolts contacts elimination (Figure 5a). These inserts will significantly reduce heat conduction but can disarrange position of free turbine in relation to housing and stability in conditions of high speed of rotation. In order to prevent this possibility, in the area marked by (c) in Figure 4 is inserted additional turbine support presented in Figure 6.

The heat radiation from the wall of flowing channel (b in Figure 4) heating inside space and reducer wall together with input shaft carrier. In order to reduce this radiation, the wall (b) is covered by ceramic foil which will reduced this radiation (Figure 5b). The thin metal wall of the channel with high temperature gas flow, gives possibility for radiation of high quantum of heat in this inside space. Ceramic foil will reduce heat radiation but it can't to be enough, and additional solutions presented in Figure 6 are inserted.

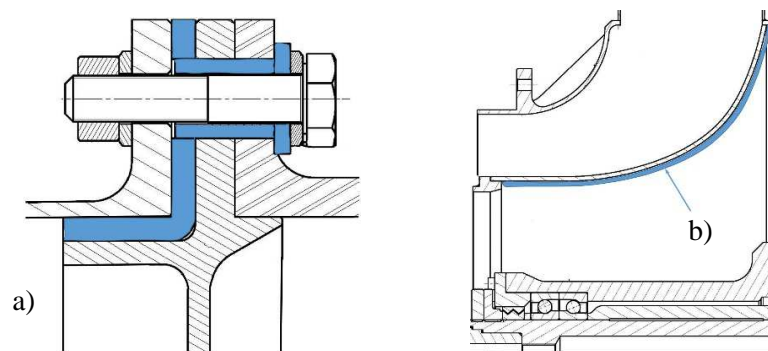


Figure 5. Isolation from heat conduction (a) and from radiation (b).

4.2. Lubrication by oil fog

Lubrication by oil under the pressure and by bilateral oil injection into the teeth mesh is suitable for maintenance of oil film between the teeth flanks and for heat taking out from the teeth mesh. In the case of very high speed bearings, big quantity of oil can increase rotating resistance and produce opposite effect. The oil mixed with the air under the pressure is more suitable in comparison with clean oil. Much less density reduce resistance and significantly increase of this mixture flow through the bearing. The stream flow of this fluid take out heat from the bearings. In the gearbox space the oil condense and air going out through outlet holes and take out some quantity of heat. For this purpose, the two branches of forced lubrication and cooling are integrated. One is for gears and output shaft bearings lubrication and cooling and another one by oil fog under the pressure, for other bearings of high speed. In Figure 6, the tubs 1 are predicted for oil fog injection in the bearing space of turbine and impute shaft. Figure 2b shows injection of oil fog in double gears bearing space.

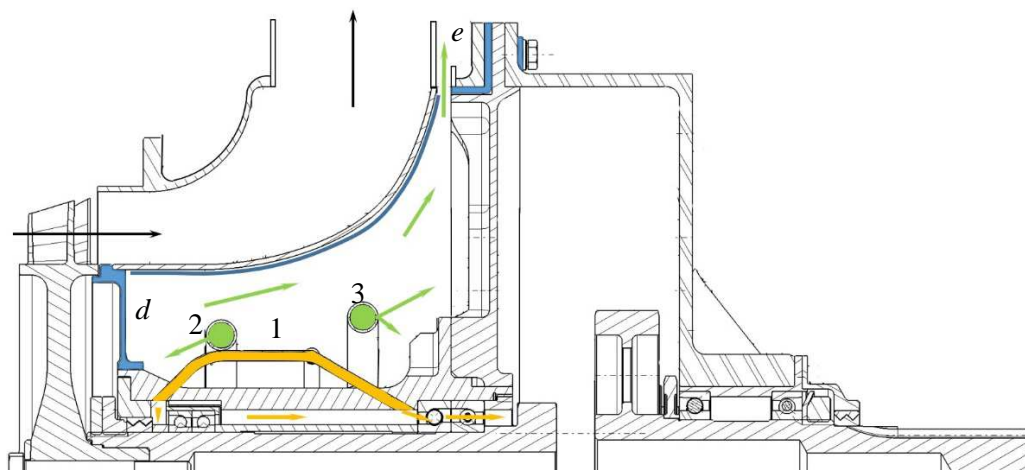


Figure 6. Heat venting from the air chamber behind reducer.

4.3. Heat ventilation

Injection of very hot gas into the space behind gearbox is prevented by installation of additional barrier-bulkhead (*d* – Figure 6) which also has the role of additional support of free turbine. This closed space is open by the set of holes (*e*) distributed around, which provides possibility for ventilation of this space. In order to make ventilation more successfully and to provide addition cooling by air, in the space are installed the two tube rings 2 and 3 which blow cold air under the pressure. This tubes are connected to turbo compressor which provides permanent injection of air and cooling of bulkhead plate and bearing carrier of input shaft.

5. Conclusion

For development of innovative design of turboshaft motor-reducer with free turbine, with compact structure, it was necessary to solve various problems. One of them is connected to installation of reducer in very hot area of gas generator and to provide possibility for maintenance of temperature level inside of reducer at the acceptable level. For this objective, in the article are presented the next results.

- The heat quantity analysis which produce gears and bearings operation inside of gearbox regardless of the side of gas generator where reducer installed. Possibilities of lubrication and cooling of gears and bearings with very high speed of rotation, are presented. Testing process and testing rig for equilibrium between produced and taken out heat is also discussed.
- Analysis of tracings for outside heat transmission to reducer installed at the hot side of gas generator, with free turbine and compact design structure.
- The set of design solution for reduction of outside transmitted heat is presented. These are solutions which have to be integrated and complement each other in order to reduce overall outside heat which can enter inside of reducer.

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