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GEAR TRANSMISSION FAILURES AND FAILURE BASED DESIGN

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Property based design - PBD approach provides improvement of various properties and characteristics. In the area of transmission units', by applyng PBD, significantly are increased service life and reliability, inclouding vibration and noise reduction. Together with these improvements, operating conditions of gear unit components got significantly worst and possible failure relations are changed and needs the new approaches in analysis in comparison to the traditional one.
This article has intention to create relation between possible failures of gearbox components, according to mentioned trends. The main trend is significant reduction of dimensions which is in strong contradiction with gear lubrication and cooling. Together with increase of rotation speed, these contradictory effects transforms pitting as the dominant gear failure into the scoring of the teeth contact surfaces. This and similar failure transitions are presented. In order to prevent it, specific cooling and lubrication systems have to be developed. This is the reason that design structure of gear transmission units getting more and more complex.
*From presented point of view, failures of gear transmission components interaction is important design constraint and it justifies the introduction of the term **Failure based Design - FBD** of gear transmission units. Presented cases study of transmission units for various applications, contains mentioned analysys and FBD application.*

***Key words**: Gear transmission units, Engineering design, Failures of gear units components*

1. INTRODUCTION

Nowadays is actual approach to increase the quality of action and behaviour of TS with existing principle of action. This Effect-based design approach is oriented to expand the domain of TS functions–***F***, domain of structures–***S*** and domain of behaviour–***B***, using integration of mechanical structure with electronic, software and mental action [1]. In Fig.1 is presented FBS model [1] with activities in all of them in the area of gear transmission units design. Also this figure shows that transformation of function–***F*** into structure–***S*** is Function-based Design which performs according to linear design model. Relation between structure-***S*** and behaviour-***B*** is Property-based design approach with the aim to improve behaviour of existing TS, according to V-design model. In order to increase the level of TS, the area of function–***F*** spreads out with electronic, software and mental action. Relation between function area–***F*** and behaviour area–***B*** is the approach Behaviour-based Design.

Perfection of TS implies the new secondary functions, the new structure and increase of TS behavior. It can be achieved by application of hybrid structure which except of mechanical, contains electronic, software and similar components, in a word by development of intelligent TS.

This kind of reverse engineering with the objective to increase existing TS behavior, performs with the pressure (force) to increase certain indicator of behavior such as efficiency, convenient control, comfort etc. The limitations which define design parameters, got *design constraints*. These are forced directions and objectives which have to be fulfilled in order to increase the level of TS. The design limitations are the passive limits which have to be satisfied, but design constraints are active and forced directions of design action and for activities which lead to objectives which are not precisely defined in advance, uncertain and will be fulfilled in the measure which allow level of knowledge, available technology and market conditions.

The basic design model established by J. Gero [1] is FBS-model (Fig.1) which shows that in design process it is necessary to bring in close relation function ***F***, behaviour ***B*** and structure ***S***. From generation to generation of power transmission units, by presented design constraints action, the level of design quality is increased, especially in the area of design behaviour in exploitation. Majority of constraints are in the strong contradictions, especially structural and behaviour constraints. The typical example is contradiction between lightweight design i.e. mass reduction and reliability and durability increase and vibration and noise reduction.

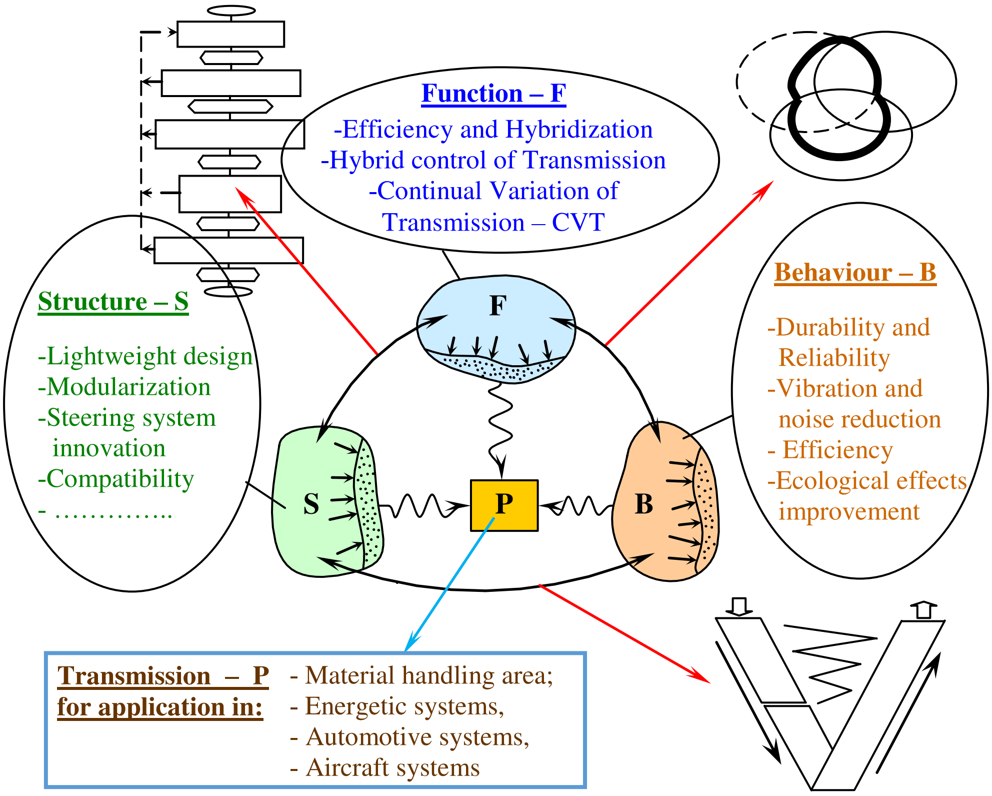

Fig. 1: Design aspects of gear transmission units, constraints and approaches

Functional design constraints in the case of vehicle gearboxes are arise in order to increase vehicle efficiency by reduction of mechanical power dissipation and to transform surplus of this power in electricity and use it when it is necessary. It was beginning of hybridization but it continued for various necessity by adding of electronic and software control.

Structural design constraints such as lightweight design and high level of compatibility, modularization, etc. got very important. These constraints are in strong contradiction between each other and with behavioural constraints. In *Lightweight design* the weight reduction is the complex activity which involves all phases of design process, starting from conceptual design, material selection, dimensions and shape selection, application of various technological methods such as thermal and plastic treatment etc. Application of these approaches can significantly reduce the mass but also can significantly increase product cost. This contradiction is very often a limit for mass reduction. *Modularization* is structural design constraint directed to the cost reduction. Modularization contains transformation of complex technical system into the set of modular components which can be installed in various design structures. Solving of this contradictions produces various specific design solutions and innovations.

Behavioural design constraints are oriented to increase quality of action, market quality, environmental and ecological quality etc. Behaviour of the system is result of developed structure and required field of functions. In reverse direction, desired behaviour imposed necessary functions, design parameters and structure, interrelations inside the system, etc. *Durability and reliability* are the main indicators for market competition. Furthermore increase of durability and reliability are in strong contradiction with other constraints such as cost reduction, lightweight design, compatibility, etc. *Vibration and noise* level reduction is also the design constraint which provides increase of TS quality and better position in the market competition. This action constrains development of technical solution which satisfies legal limitations and also in reverse, provides effect at the legal limitations to be stronger in the future.

Satisfaction of design constraints cause change of operating conditions of gear unit components. Speed of rotation, loads and stresses significantly increases. The space for components installation and surface for heat reflection, decreases. These are conditions for gear teeth failure transition from pitting to scoring. Lubrication of gears and bearings together with cooling needs specific approaches which can significantly increase design complexity and cost. This is the trend in all areas of gear transmission units' application: material handling, energy production, automotive and aircrafts. The intensity of contradictory interaction are not the same and effects are the different and design solutions are also different.

Failure-based Design-FBD is result of worsened conditions and endeavour to avoid any kind of failures. This means if these contradictions cause the new kinds of failure, to find some kind of design approach and solution which can prevent expected and possible failure. This is the set of design activities which provide reliable and steady operation of gear transmission unit.

2. TRANSITION OF GEAR UNITS FAILURES

By application of design constraints presented in Fig.1, operating conditions of gear units components getting worse and worse. Reduction of dimensions significantly increase the loads and stresses. Together with very high speed of rotation and reduced volume, heating inside of gear unit, makes extreme difficult ***operating conditions***. This transition of operating conditions causes transitions of component failures.

Gear failures, very known, tested and recognized in standards for gear design, transit from the state which provides usual gear unit behavior (vibration, reliability, etc.) to the state of progressive damage and reduction of service life. Its' need additional design improvement with the aim to prevent effects such this one. In Fig.2 is presented possible trends in gear teeth failures in relation to load limits according to various failures. It is known that involute teeth fracture limit is higher in relation to teeth flank failures. Teeth pitting load limit is common for gear design. For this purpose it is necessary to provide lubrication with permanent and stabile oil film in teeth contacts and corresponding pressure and stress distribution (Fig.2). Missing of oil film transit teeth flank failures from pitting or micro-pitting to spalling (in the range of small speeds) or to scoring in the range of high circular speeds. Losing of oil film in conditions of high speed and high load produce local welding and particles and pitting roughness's produces very intensive scoring process, overheating and reduction of service life. In order to avoid losing of oil film it is necessary to apply corresponding lubrication system. Gear sinking in oil (Fig.3a) can provides oil film for relative small speed and stabile gear unit position, not in vehicles and aircrafts. Centrifugal effects produces oil dispersion and it is not possible to create oil film when the speed is high. Spraying by oil under the pressure provides possibility for stabile oil film and for teeth cooling (Fig.3b). When peripheral speed is very high such us 80m/s and more, centrifugal effects can prevent possibility of oil film creation. For these conditions oil film can be survived by bilateral spraying of gear connection area (Fig.3c).

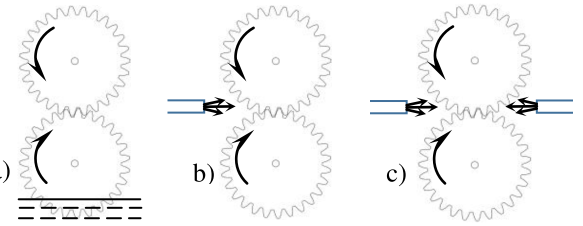

Fig. 3: Principles of lubration and cooling

Lubrication by spraying (Fig.3b and c) provides possibility to avoid scoring failure but makes design structure much more complex and expensive.

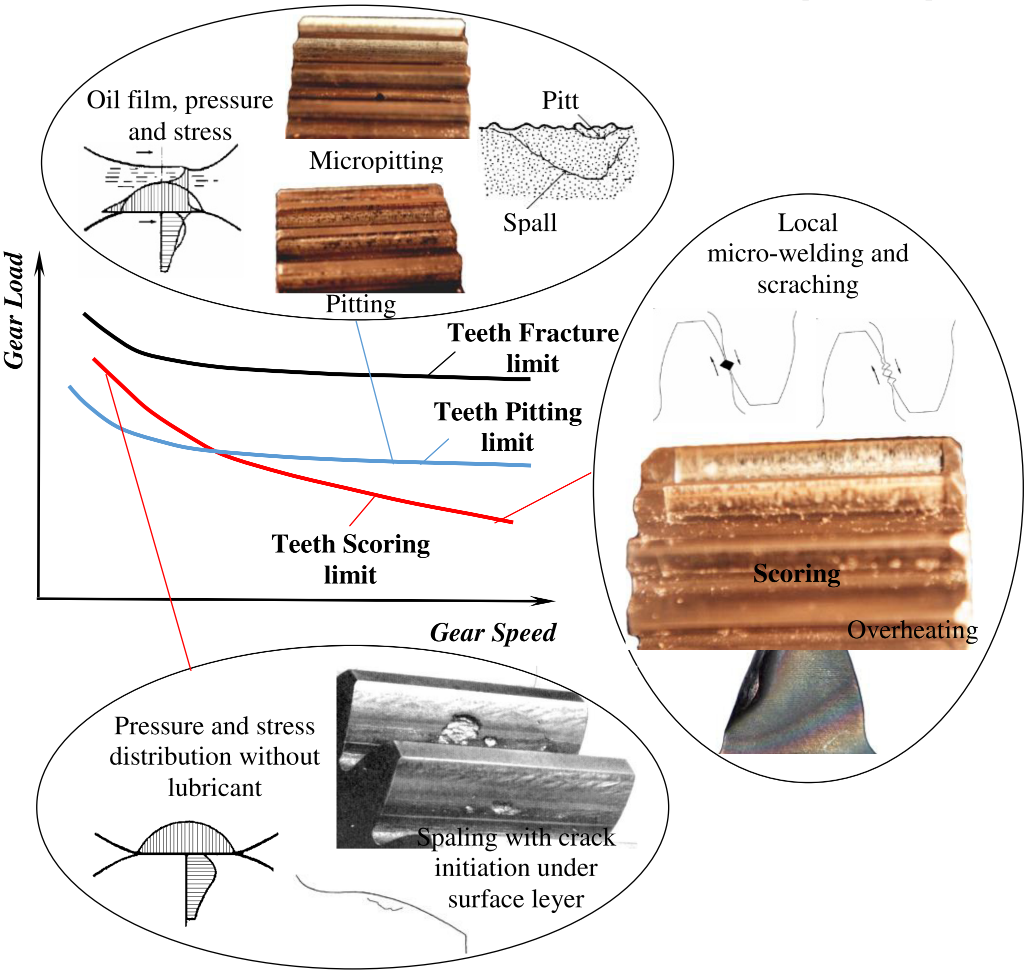

Fig.2: Relation between types of failure, gear speed and gear load limit

Bearing failures do not significantly transits in those extreme operating conditions but the service life has reduces. Reduction of gear dimensions increase bearing loads and necessary bearing dimensions. The main contradiction in lightweight design that reduction of gear dimensions is limited by the necessary space for bearings. Approach in design to solving of this problem is specific. For this purpose various kinds of bearing designs of small volume and high speed is developed. Additional problem is that this solutions needs specific way of lubrication and cooling. Furthermore, rolling bearings for extreme operating conditions replace hydrostatic, aerodynamic or aerostatic plane bearings.

Caring structure failures in the new designs are important for analysis. Lightweight design together with design volume reduction impose the need for design of complex shape and light caring structure of gear units. Inside structure of gear unit getting complex and compact. It is not easy to make difference between the shafts and gears (see Fig.5-7). Also housings are made from lightweight alloys, have small wall thicknesses with a lot of ribs. The ribs have to increase housing strength and stiffness. Reduction of gear dimensions has effect to increase gear forces and bearing and housing loads. In contradiction to reduce housing mass arises possibility of the ***crack initiation in the housing walls***. Together with residual stresses as a casting result, the crack initiation in the housing walls getting very probable.

Reduction of dimensions reduces housing outside surface for heat radiation. The ribs provides relative small improvement but very often it is not enough. Really high quantity of heat relished inside of gear unit has to be taken out using additional design solutions.

Gear resonances in the case of high speed of rotation are also probable. Gear rotating masses connected with gear teeth in mesh stiffness presents harmonic oscillator. When teeth mesh frequency comes close to natural frequency of harmonic oscillator, arises gear in mesh resonance. This resonance produces significantly increase of dynamic loads of complete structure and level of vibrations. Gear transmission units consists of a few gear pairs in mesh and everyone has teeth mesh resonance. Additionally gear unit structure has modal shapes of natural vibrations. Teeth mesh frequencies of gears have to be different in relation to natural frequencies. From this point of view, dynamic analysis of gear unit with high speed of rotation is really complex for analysis.

3. FAILURE-BASED DESIGN

Property-based design is general approach in engineering design oriented to improve certain property of developed or existing technical system. The set of technical system properties identify behaviour-B of the system (Fig.1). In order to increase the level of TS behaviour, relation between structure-S and behaviour-B is the task of Property-based design which is carry out according to V-model presented in Fig.1. Since the possible failures belongs to the group of design properties or indicators of design properties, Failure-based design corresponds to this design approach.

Property-based design with the task to increase TS reliability, to increase aesthetic level, to reduce vibrations and noise, etc., presents the set of minor or large design activities which lead to the aim. Failure-based design also contains the set of design activities which correspond to technical system type and to failure or cause of failure. In Fig. 4 is presented this procedure which consists of a few groups of activities. The first group includes analysis of operating conditions, causes of failures and failure processes. Systematic search for details of causes is the base of search for the solution which can prevent certain failure. The next group of activities is search for these design or other solutions by application of innovative technics such as TRIZ or WOIS. Since the failures are results of no harmonized contradictions in technical systems, the TRIZ technique leads to contradiction harmonisation and WOIS leads to solution without compromise. Both imply perforation of thinking barrier and search for the new innovative solution. This means spreadsheet area of function-F, structure-S and behaviour-B. The thread group of activities is development of the new design structure with improved mechanical structure, electronic structure and software. This is enhanced existing TS or the new one and present higher level of TS perfection. The fourth group of activities, according to Fig. 4, contains systematic conditions analysis and testing in relation to expected influences. For this purpose the process needs various models and experimental installation for simulation of conditions in service life. Very often results of these analysis are not satisfactory. In the meantime information and knowledge level got higher and the next iteration of failure-based design procedure can be successful. This means that procedure is iterative and every iteration leads to higher level of TS perfection.

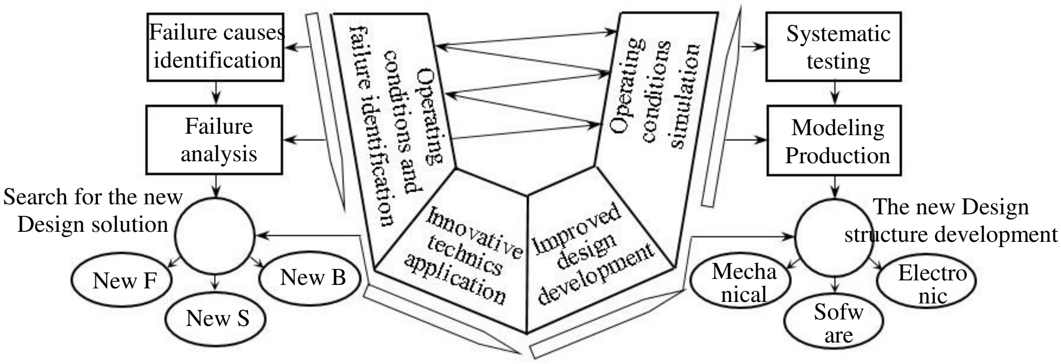

Fig. 4: Failure-based Design procedure

4. CASES STUDY

The set of innovative gear units are developed according to presented methodology. Principles of development are the same but depending of operating conditions and design constraints, the results are with design specificity.

4.1. Area of energetic systems

Production of electricity from alternative resources makes wider the area of gear units' application. Various functions have to be carried out by gear units. In Fig. 5a is presented gear unit applied at wind turbine. In combination with electronic system and motor-generator, gear transmission variates transmission ratio according to wind speed in order to provides permanent speed of electricity generator and 50Hz current, ready for synchronization at public electric net. Mechanical part of this hybrid system consists of the two planetary stages. Outside gear ring at the second stage is not fixed. By motor-generator this ring rotates with the speed which corresponds to necessary transmission ratio in dependence of wind speed. Motor-generator tracking or braking gear ring, spend or produces electricity using additional batteries.

Mechanical structure is developed according to lightweight design principles. Materials, dimensions, shape, volume and other features are selected to provide minimal mass and volume of complete structure. That is the reason for possibility of mechanical failures especially at gears and bearings. Sinking of gears in oil provides lubrication of this relative slow gears. Cooling of this compact gearbox is solved by specific solution using heat superconductors in the form of sheets which covers gear unit and outside turbine box. This solutions provides possibility to avoid gear failure in the form of scoring and put back to the pitting (Fig.2). In Fig. 5c is presented testing installation with power circulation and load, speed and transmission ratio variation for testing to the failure arises, by operating conditions variation according to service conditions.

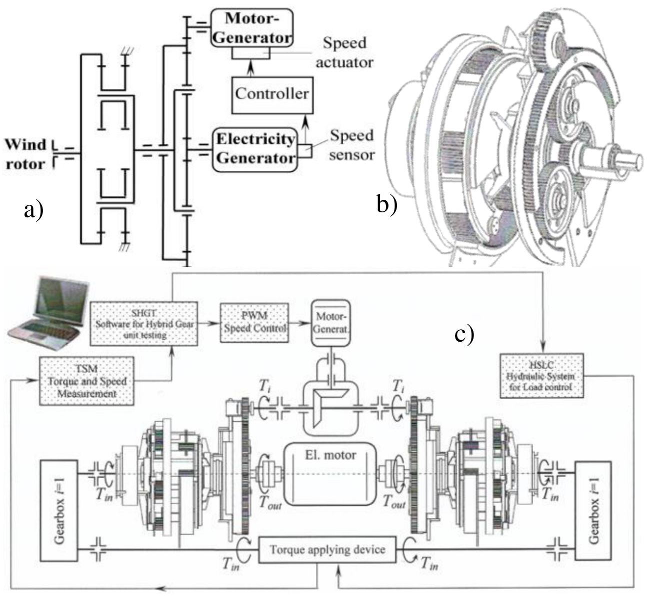

Fig. 5: Wind turbine gearbox with continual variation of transmission ratio: a) turbine concept, b) gearbox design, c) test installation with power circulation

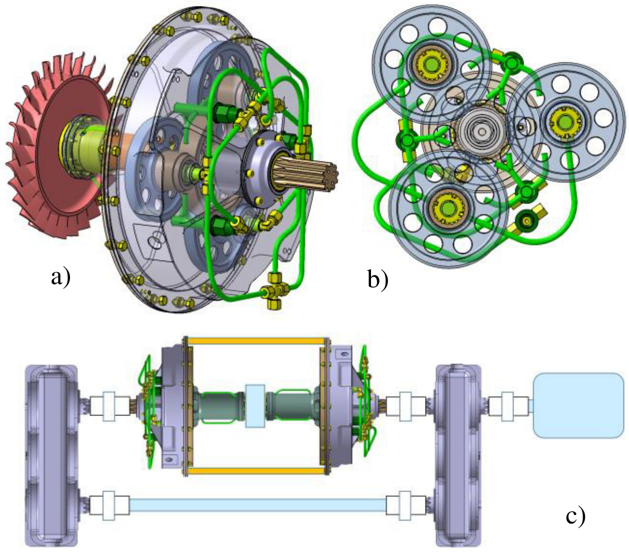

Fig. 6: Reducer of turbo-shaft motor: a) reducer design, b) bilateral lubrication of gears, c) test stand with power circulation

Electricity production from biomass fuel can be carried out by gas-generator and turbo-shaft motor. Very high speed of rotation, 40.000-65.000 rpm have to be reduced to the level of 6000 rpm suitable for electric generator operation. Design solution of reducer for this purpose is presented in Fig.6a. Peripheral gear speed of input gear is higher than 100 m/s. In order to maintain the oil film between gear flanks is applied bilateral oil injection in gear meshes (Fig.6b). Besides of oil film provision, the oil has the task to take out significant quantity of heat produced in the teeth contacts. For carrying out these functions reducer has to be equipped with hydraulic oil system and with cooling system. The question is the optimal balance between reducer volumes, speed and load capacity in relation to additional complex equipment which it is necessary to apply in order to avoid gear scoring and provide conditions for pitting failure (Fig.2). In Fig. 6c is presented the test stand for reducer testing until to failure according to principle of Failure-based design presented in Fig.4. The stand consists of the two opposite connected reducers with input shafts. Output shafts are connected to the gearboxes which provide power circulation, speed of output shafts of 6000 rpm and corresponding load. Test stand is equipped by system for lubrication and cooling and by system for operation conditions monitoring. Testing prolongs until to the gears failure with testing time not less than expected reducer service life.

4.2. Area of automotive application

Innovative design of automotive hybrid gearbox with continual variation of transmission ratio 1...10 is presented in Fig.7. This is the two stage planetary transmission connected by motor generator which consumes and produces electricity in the course of transmission ratio variation. Gearbox is extreme compact with outside diameter about 300 mm, transmission power 315 kW and input speed 6000 rpm. Gears operates with very high speed and are in very high risk of scoring failure. It is necessary to find out solution for lubrication and cooling in order to avoid scoring failure.

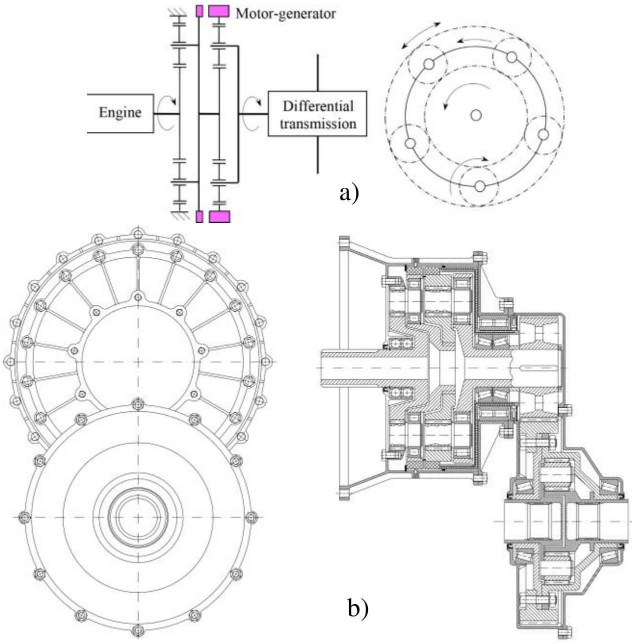

Fig.7: Hybrid design of automotive gearbox with continual variation of transmission ratio

4.3. Area of aircrafts

Design constraints presented in Fig.1 in the area of aircrafts are of significant importance especially lightweight, reliability, vibration etc. Power sources are of extreme high speed and specific loads of transmission unit parts are also high. Turboshaft engines provides high level of power with extreme high speed of rotation and have relatively small mass. Helicopters or propeller airplanes needs 20…100 times less speed of propeller rotation. Very light and reliable gear units have to provide corresponding speeds. In Fig. 6 and 8 are presented gear units for this purpose. In Fig. 6 is presented gearbox for turboshaft engine which can be used for propeller aircrafts propulsion or for ground energetic application. In Fig. 8 is presented design for additional speed reduction for helicopter propulsion. Both of them need application of Failure-based Design approach (Fig.4) in order to find corresponding design solution which will provides gear pitting failure instead of scoring failure. Lateral or bilateral forced lubrication (Fig.3) and conduction of teeth local heat is the main target of design. Delivery and return of oil together with the cleaning and cooling is the task of complex oil system with the pumps, oil tank, filters, valves etc. (Fig.8). The main topic in design and testing of this gearboxes is transferred from the gears and bearings to lubrication and cooling system, very important for reliable operation.

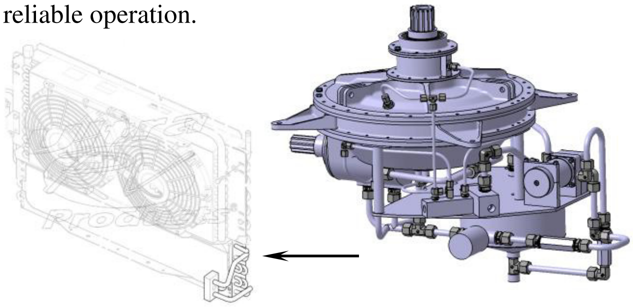

Fig. 8: Additional design structure applied for lubrication and cooling which provides gear unit operation in aircraft field

5. CONCLUSION

Actual design constraints in the area of gear transmission units such as continual variation of transmission ratio, lightweight, reliability, vibration, etc., cause transition of failure processes and also present the top topic of gear units design. The article offer the next contributions.

1) Transition of gear teeth failure process caused by application of actual design constraints.
2) Failure-based design of gear units in order to prevent failure transition from gear pitting to gear scoring.
3) For energetic application, in the area of alternative sources of electricity (wind energy and biomass), the two innovative gearboxes are presented and discussed.
4) For automotive and aircraft areas are also presented innovative designs of gear boxes together with discussion according to presented methodology of Failure-based design.

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