Joanna MATCZAK, Kamil MATCZAK

DYNAMIC ANALYSIS AND EARLY DAMAGE DETECTION IN CYCLO GEAR BOX

W artykule omówiony został problem drgań oraz wczesnego wykrywania uszkodzeń zmęczeniowych w przekładni typu cyclo. Przedstawiony został model dynamiczny stworzony do badań trwałości zmęczeniowej węzłów tocznych oraz trwałości zazębienia obiegowej przekładni cykloidalnej, a także pomiaru drgań. Szczególną uwagę poświęcono budowie przekładni cykloidalnej oraz poszczególnym elementom modelu numerycznego. Przeprowadzono analizę dynamiczną dla wybranych komponentów przekładni przy pomocy programu Inventor Proffesional 2017.

INTRODUCTION

Cycloidal gearing are commonly used in the industry as manipulating robots, positioners cooperating with robots, CNC machining centers, revolving trays of tools and rotary tables also used in machine tools, woodworking machines, textile machines and glass machines. In addition, they can be found in medical technology and transportation systems. They are an important element in these machines and equipment, contributing greatly to their safety. Destruction or transmission components wear may cause long-term detuning work, requiring replacement of individual components with new ones. Therefore, transmission components must meet particularly high requirements for their durability, and reliability. In the design process we need to achieve the highest value relative power transmitted through the wheels to the mass. Controlling design and operation process of machines require using of appropriate methods of diagnosis in order to prevent potential failures. The purpose of diagnosis is to detect defects and irregularities of the gear unit. Detection of defects and other irregularities transmission operation is carried out by monitoring and analyzing vibration signals, temperature, analysis of the products resulting from damage. Heavily loaded gear should be temporarily or permanently monitoring to ensure safe operation. Techniques for diagnosing the technical condition of gear are focused on the identification of the defect in the initial phase.

In many scientific centers people are working in order to create the appropriate tools to support processes of recognition of damage, especially in their early stages diagnostic studies of real objects encountered at various stages of wear and damage to the transmission components. Presented in the literature guidelines for conducting the measurement and interpretation of results in the case of damage to individual components, may be insufficient for correct diagnosis of complex lesions. Methods of diagnosing gear should allow the determination of the technical condition of various independent elements, for example: the state of cooperating wheels and rolling bearings.

1. EARLY DAMAGE DETECTION

1.1. Early damage and fatique tests

Planetary gears due to the growing interest in them many centers, they become an ideal object of diagnostic tests for detection of damage cycloid wheel and roller bearings. Damage to the gear elements are connected often with vibrations. In the case of planetary gears main source of vibration and noise are planetary gears and bearings. These are the elements that must be characterized by high durability and reliability, to evaluate the technical condition of the used diagnostic vibroacoustical, which typically involves measuring the velocity of the body (the measurements are usually near the bearing) and analysis of the frequency of the vibration signal (within the determined, among others, frequency spectrum and the spectrum envelope of the signal). One of the most commonly used methods is to measure the vibroacoustic signal and to determine on the basis of measurements are sensitive to various types of damage. The rate of spread of the vibroacoustic disturbances caused by the change in the gear, the vibroacoustic methods are particularly useful in the diagnosis of early stages of damage.

Nowadays greatly developed techniques non-contact vibration measurement. They allow measurement of the speed of vibration of rotating elements. Measurements of velocity rotary shaft allow the elimination of the impact of the complex and variable during the transmittance of the bearing-body gear. An important issue in diagnosing transmission is the ability to distinguish between the impact on signal NVH various phenomena related both to its normal operation as well as changes caused by damage to the development of its elements.

Vibration measurements are made in order to:

- location of vibration sources and the search for the causes of their occurrence,
- assessment of tooth wear gear and control vibration phenomena that may cause the wear,
- assessment of a vibrating- current state and comparing it to the state of the transmission,
- collect data for a full analysis of a vibrating- current status and comparison,
- prediction about future states of the technical
- indicate the reasons causing the deterioration of the vibration transmission,
- provide recommendations on the procedure to minimize vibration transmission.

Causes of the vibration transmission are usually divided into external (due to the impact of the gear working machine and motor) and internal. External forces we cannot avoid. With the appropriate choice of fastenings can get their reduction. The values of vibrations caused by internal reasons, we are unable to modify.

There are three main groups of causes of vibration transmission:

- design- speed, nominal transmission load, stiffness, bearing lubricant characteristics, the frequency of meshing, vibration own gear, body design;
- regulations - the deviation direction of the line of the tooth pitch deviations, tooth profile modification, assembly accuracy, fit bearings and their initial tension.

– interfere with the movement of the gear - change meshing stiffness, damping meshing when buttresses, the deformation of teeth due to load unbalance planetary gears, changing the conditions of cooperation wheels correlated with consumption of planetary gears.

The most important source of vibration are errors (inaccuracies) executive wheel cycloid, excitation arising from the entry and exit teeth meshing and meshing stiffness variations. In order to reduce the impact of these factors apply:

– correction of gear accuracy,
– making appropriate modifications to the shape of the tooth, which reduces the impulses caused by intermeshing (changes the shape of the tooth profile by introducing modifications to the longitudinal and transverse adapted to the loads carried and adequate to the expected deformation of teeth, the most widely used toothings custom to bring out the reduction of noise emissions from noise and vibration are gearing high) .
– increasing the meshing rate- smallest / largest number of pairs of teeth which are also in the buttress (use of non-standard gear, due to the state NVH transmission seeks to value ratio gearing was equal to an integer greater than 1, the increase in the value of the indicator mesh is possible by choosing the appropriate the geometrical parameters of gearing, ie. the tooth module, number of teeth, the sum of the coefficients shift tooth profile, Pressure angle and height of the teeth).

The above-mentioned ways to reduce the generation of vibrations through the gears have a specific justification in their simultaneous application. In many cases, the scope of application, require the use of high teeth, otherwise there is a possibility of significantly reducing the value of the indicator. [8]

Generated by the gear vibration they can be considered in terms of tending to determine the dynamic load elements (gearing, bearings, shafts) of the draft gear or in terms of diagnosis, and therefore aimed to determine the current and projected state of technical gear utilized in the drive work machine.

Reviewing the literature, we can conclude that the current state of knowledge does not recognize fully the issue of the impact of individual parameters of the transmission (e.g. mesh stiffness, damping gear) at its dynamic activity.

The main task of operational diagnostics gear cycloid is to detect degradation processes and consumption in the early stages, before they lead to failure. From previous research it shows that most of the failures of gears are caused by damage to the teeth, and about 90% of these lesions is local damage such as fracture at the base, partial chipping and short-term and fatigue fracture, pitting, scuffing, Scaling. Cycloidal gearing are used to carry a significant load are particularly exposed to high dynamic forces. Impact on the dynamics are sources of external and internal gears. The main parameter of the internal with a significant impact on the course of dynamic processes in the gear teeth is periodically variable meshing stiffness. Study of the effect on the rigidity of the meshing of dynamic processes occurring in the cylindrical gear can be carried out by testing the actual object or by means of mathematical models. The stiffness of the mesh is associated with the currently occurring number of teeth in mesh. At the time of working, only one pair of teeth (meshing Single pair), they undergo the greatest deflection, which causes the wheel is driven delayed with respect to the driving gear by the amount of deflection of the measuring section along the length of buttress. At the next couple of teeth enter into the engagement, the load is concentrated in one pair of teeth is distributed now on two pairs of teeth. Deflection as measured along the length of buttress is reduced by about 50% relative to the deflection occurring in engagement of one-pair. Then, after leaving one pair of engagement with the deflection of the remaining vapor increases almost doubled. In this way the rotation of the wheels is applied to the oscillatory motion, which accelerates or retards the movement of the wheel driven. Therefore, an important issue in the design of the gearbox is to conduct dynamic analysis takes into account the variable meshing stiffness and other parameters affecting the dynamic forces.

1.2. Computer analysis

The development of computer hardware and signal processing methods enable the use in the process of diagnosing advanced methods of signal analysis at the level of time-frequency. These methods allow follow-time, pulse signals disorders caused by lesions in their early stages. Method for the simulation of dynamic models of transmissions is particularly useful because it allows you to quickly, without the need for complex laboratory tests to study the impact of design parameters and technological progress of dynamic phenomena in planetary gears. This method makes it much easier, and sometimes it is the only method that allows assessment of the influence of qualitative and quantitative generated by external sources and internal vibration transmission components to its dynamic state. Experimental studies gears are difficult to implement, costly and time-consuming, and in case of transmission produced individually, often impossible. In such cases, it is appropriate to use the identified dynamic model gear in the drive system. It will enable a series of numerical experiments and analysis of simulation results allows for an increase in the diagnostic knowledge and gain greater certainty of diagnosis.[5]

It was decided to carry out research using computer-aided, using the method of numerical simulation, which seems to be the most adequate to carry out the analysis. The knowledge gained will enable engineers to design gear cycloid optimal due to their dynamic state, and will allow for early detection of damage to individual elements of transmission.

To perform numerical analysis used a model for the study of dynamic phenomena occurring inside the transmission. The vibration transmission (amplitude spectrum) are dependent on inter alia: the stiffness of meshing construction errors and assembly, as well as the size of the transmission. It was assumed that the transmission is burdened with constant torque at the input and output. We conducted a thorough analysis of the transmission isolated from the drive system, in which only causes the dynamic loads are the sources of internal and external load is fixed (constant torque, causing the movement of the input shaft). Transmission was treated as an object isolated from the influence of the working machine, which has been thoroughly mapped meshing property by assuming nonlinearity characteristics of stiffness and damping, as well as the impact of backlash on the dynamic load generated in the meshing gears.

Stress analysis and dynamic analysis can be divided into several stages. The first stage is to create a geometrical model in the 3D design (in this case: Autodesk Inventor 2017). In the next step the previously prepared model should be divided into finite elements. This can be done both in the program used for the calculation of finite element method (eg. ANSYS, FEMAP), as well as using the program for 3D design, or in the program used to generate the finite element mesh, for example. HyperMesh, and then move the grid to the program in which we will carry out calculations. In the next step should be applied boundary conditions, such as load fulcrum point of contact, so that the model had respectively received the degrees of freedom and appropriately modeled and defined load contacts. The final step is to analyze the results obtained from the calculation.

2. CYCLOIDAL GEAR

2.1. The construction and operation of cyclo gear box

Speed Reducer is the gearbox, which comprises of gears mounted on shafts, supported by bearings, assembled in a lubricant-tight enclosure, sealed on both ends.

Their function is to convert high-speed rotary input power, which has a low torque, to a proportionally low-speed, high-torque output power, for use in mechanisms of machines to perform work. The ratio of output and input speeds is the transmission (or speed) ratio. Gear transmissions are required for basic reasons such as: inertia matching, speed reduction and torque magnification.

Since motors cannot supply the required high torque for the given input power, a speed reduction unit (gearbox) is a basic equipment placed between the motor and the driven machinery. A gear transmission system is a device used to transmit mechanical rotary power from one shaft to another by increasing torque and reducing speed simultaneously or vice versa.

Used K-H-V is special gear which allows to obtain high gear ratio at one stage, known as the cycloidal gear. In terms of construction it is a rolling gear, in which all the elements with interlocking connections move in rolling motion. This construction system is designed to reduce the losses, which are caused by friction. Planetary gear has the geometry axes of wheels movable relative to the base. The consequence of this is a significant increase in the coefficient of mechanical efficiency and increase system reliability. The objective gear is shown in Figure 1 [2, 3, 4].

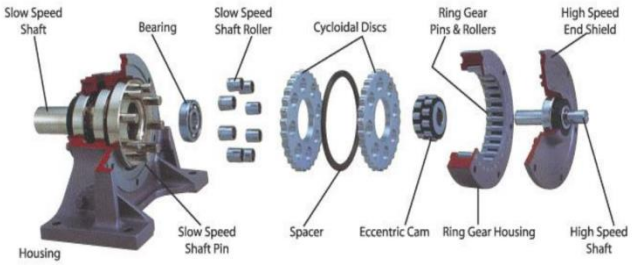

Fig. 1. *Cycloidal gear [8]*

Cycloidal gearing can be significantly overloaded. They provide higher uniformity of movement. Compared to the conventional gears with the same ratio they are characterized by high compactness. The advantages are: low noise vibration and a very small angular clearance. They are used among others: machine tools, textile machines and glass, woodworking machines, medical technology, transport systems, handling robots, positioners cooperating with robots, CNC machines, turret trays tools and rotary table.

$$\mathrm{i} = \frac{z1}{z2-z1}; \qquad (1)$$

Where:

a) z1 – number of teeth in stationary wheel,

b) z2 – number of teeth in movement wheel (cycloidal).

The difference in gear number of teeth $\Delta z = z2 - z1$ equals usually 1 (rarely 2).

Consequently, the equation (1) becomes:

$$\mathrm{i} = \frac{z1}{1} = z1 \qquad (2)$$

with the result that the gear of this type it is possible to obtain a large gear ratio [6]. A three-dimensional model of the transmission shown in Figure 2.

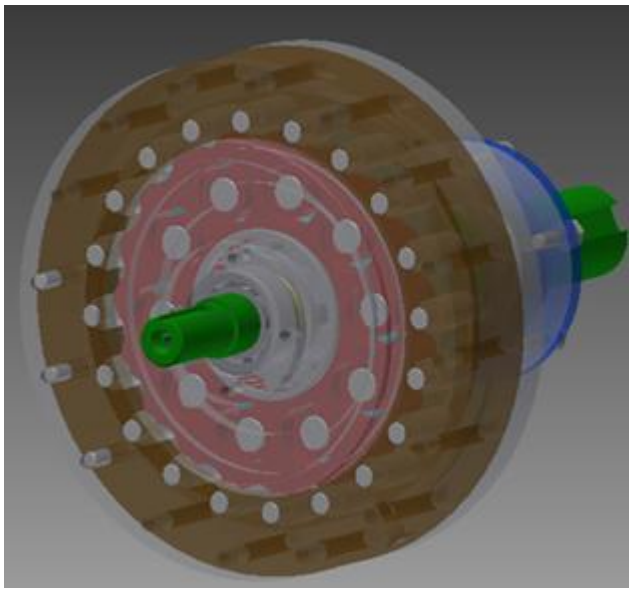

Fig. 2. *Digital model of used cycloid gear.*

Distinguished roller pairs are the following: planet gears co-operating with rollers (forming a cycloid gear engagement), the rolling sleeve to the planetary gear bore and the cylindrical roller bearings mounted in the central opening of the planetary gear. All the rolling elements in a power transmission made of alloy steel [1]. For the balance of forces and mass reduction of the forces between the toothed uses two identical planet gears turned by an angle, due to their lateral position to each other and the construction of eccentric (shown in Fig. 3).

Internal gear engagement create planetary wheels and cooperating with them stationary sun gear. Planet gears are toothed externally, the outline of the tooth is formed equidistant shortened. Properly adjusted outline of the tooth allows you to work with a difference number of teeth in the two-wheeled co-operating. In the circular gear formed a central hole, used to eccentric rear wheels (Fig. 4), by the cylindrical roller bearing on the shaft active. Immobile central wheal creates a roller assembly, a straight-line mechanism is a shield with pins. The main elements that combine all the elements together are planetary gears [2, 3, 4].

Fig. 3. *The central wheels laterally offset relative to each other, as a result of the eccentric shaft..*

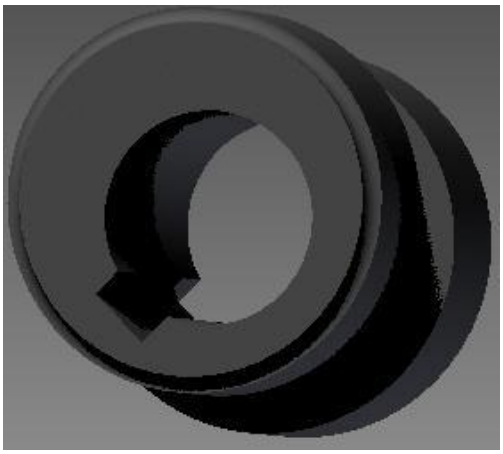

Fig. 4. Eccentric

The system movement is forced by the rotation of the eccentric bearings, which drives the pinion gearing. Quantity and the outline of the tooth movement force in such a way that one full rotation of the input shaft causes rotation of the wheel cycloidal of one pitch in the opposite direction. Thus the cycloidal gearing perform rotary motion with the speed reduced. Turnover are transferred to the output shaft by means of pins cooperating with holes in the wheels. Also this connection can take place by means of rotary elements. The use of a cycloid tooth-profile allows for the simultaneous engagement of multiple teeth.

The research strength and fatigue life of wheels outline equidistant finite, in determining damage, such as damage to the meshing for example: consumption cratering, there is a need to determine at what time they occur from the first run the machine at a given load size. A kind of consumption for the durability of this type of gear is fatigue wear. This is confirmed by the initial prototype testing Cyclo gear [7].

Sun gear (Fig. 5) is subjected to the composite system of loads, which results from gear work, so its geometry may vary under the influence of loads and improperly selected material. It is also important for the correct formation of wheel selection by the tolerance of properly established technology of manufacture. Durability of cycloidal gear, is conditioned durability weakest kinematic pair in a transfer of power. Thus, the stability of each cycloidal gear rolling pair also depends on the state of the load [2, 3, 4].

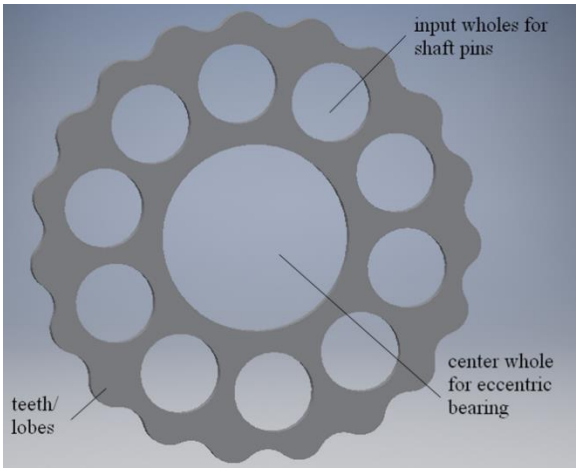

Fig. 6. Sun gear

In the researches of strength and fatigue of the wheel's lynx equidistant finishing, in determining damage, such as: meshing damage, pitting expenditure, there is a need to determine at what time they occur from the first run the machine at a given load size. A kind of consumption for the durability of this type of gear is fatigue wear. This is confirmed by the initial numerical cycloidal gear testing [7].

2.2. Numerical testing

Fatigue strength test of rolling couples of complex shape cooperating surfaces carried out numerically. The biggest problem was the programming of complex load contact. Therefore, to study the fatigue life of meshing cycloidal used, the prototype copy of the Cyclo gear. Dynamic tests were conducted at a given load and constant speed drive shaft.

In this paper authors focused only for heart of cyclo gearbox-input shaft, satellites, bearings, sleeves and eccentricity.

Modal analysis with Autodesk Inventor Professional 2017, results for Shaft:

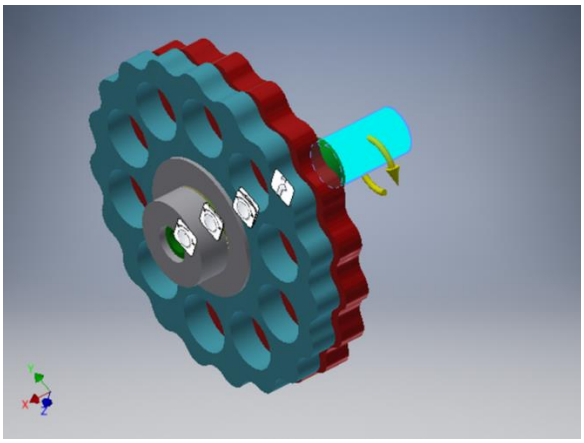

Fig. 7. Digital model- input shaft with satellites

Tab. 1. Material properties

Model information:

Material used for the model	Different kinds of steel
Density	7,85 g/cm^3
Mass	1,04472 kg
Surface area	161057 mm^2
Volume	575004 mm^3
The center of gravity	x= 118,365 mm y = 23,3229 mm z = 0,00716966 mm
The type of researches	Modal analysis
Number of models	8
Frequency range	0-50
Type of load	Torque: 240000 Nmm

Name of the part	Shaft
Material Name	steel high-strength, low-alloy steel
Yield strength	275,8 MPa
Tensile strength	448 MPa
Young's modulus	200 GPa
Poisson's ratio	0,287 ul
Modulus of elasticity	77,7001 GPa
Name of parts	Eccentricity Sleeves Bearings Satellite
Material name	mild steel, welded
Yield strength	207 MPa
Tensile strength	345 MPa
Young's modulus	220 GPa
Poisson's ratio	0,287 ul
Modulus of elasticity	86,2745 GPa

Assumption: frequency: 0-50 Hz. Torque: 24000 Nmm.

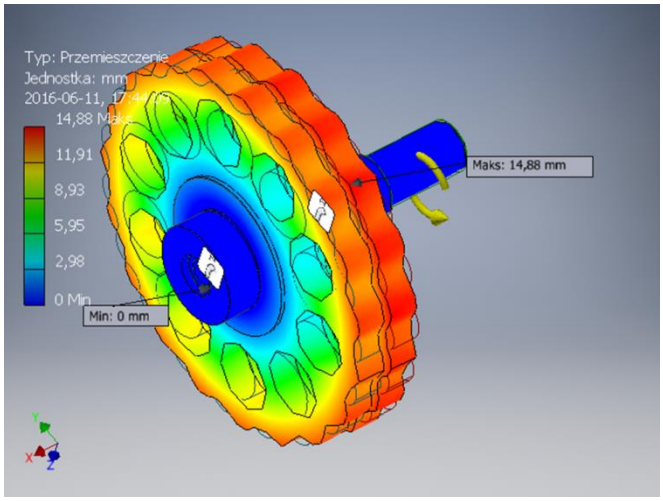

Fig. 8. *Total displacement*

According to the calculations of the input shaft deformation will occur at a frequency F1 = 1846.49 Hz, ie 110760 rev / min.

SUMMARY

The article presents an analysis of the dynamic gear for the selected item. Research carried out for all elements will allow you to determine which part of the transmission is overloaded during operation and which pair of rolling turns out to be the least durable. Numerical investigations of other transmission components will be presented as a separate paper.

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Dynamic analysis and early damage detection in cyclo gear box

Paper discussed the problem of vibration and early detection of fatigue damage in the cyclo gear type. It was presented dynamic model created to study the fatigue life of rolling pairs and durability meshing Cyclo gear, and vibration measurement. Particular attention was paid to the construction of cycloidal gear and the individual elements of the numerical model. An analysis of the dynamic for the selected gear components using Inventor Proffesional 2017.

Authors:

mgr **Joanna Matczak** – PhD student– Lodz University of Technology, Department of Vehicles and Fundamentals of Machine Design

mgr **Kamil Matczak** – PhD student– Lodz University of Technology, Department of Vehicles and Fundamentals of Machine