APPLICATION OF THE LOCAL MESHING PLANE IN DETECTING ASSEMBLY AND MANUFACTURING ERRORS OF GEARS

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Summary

In the paper application of the local meshing plane concept is discussed and applied for overall gear quality assessment. Knowing the kinematic properties of the machine (i.e. gear teeth numbers) it is possible to modify the gearbox vibroacoustic signal in such a manner that its fragments will be linked to different rotating parts. This allows for presentation of a raw or processed gearbox signal in a form of three dimensional map on the plane "pinion teeth x gear teeth" called local meshing plane. Meshing plane in Cartesian coordinates allows for precise location and assessment of gear faults in terms of meshing quality of consecutive teeth pairs. Although the method was applied to simulated signals generated by a gearbox model, similar results were obtained for the measurement signals recorded during the back-to-back test stand experiment.

Described method could be used for assessing the manufacturing quality of gears, the assembly quality as well as for the fatigue gear failure evaluation during normal exploitation.

Keywords: gears, gearbox diagnosis, local meshing plane analysis, nonstationary signals, fault diagnosis, gearbox modelling.

WYKORZYSTANIE LOKALNEJ PŁASZCZYZNY PRZYPORU W WYKRYWANIU BŁĘDÓW WYKONANIA I MONTAŻU PRZEKŁADNI ZĘBATYCH

Streszczenie

W artykule przedstawiono możliwość wykorzystania lokalnej płaszczyzny przyporu do oceny jakości pracy przekładni zębatej. Znając własności kinematyczne przekładni (tj. liczby zębów kół) możliwe jest takie przekształcenie sygnału wibroakustycznego emitowanego przez przekładnię, że poszczególne jego fragmenty będą związane z kinematyką wirujących wałów. Pozwala to na przedstawienie oryginalnego lub przetworzonego sygnału w formie trójwymiarowej mapy na płaszczyźnie „zęby zębnika x zęby koła" nazywanej lokalną płaszczyzną przyporu. Płaszczyzna przyporu, we współrzędnych kartezjańskich pozwala na lokalizację i ocenę uszkodzeń przekładni poprzez ocenę jakości poszczególnych przyporów wszystkich par zębatych. Metodę zaprezentowano na przykładzie sygnałów generowanych przez model symulacyjny przekładni zębatej oraz zweryfikowano na stanowisku mocy krążącej.

Opisana metoda może być używana zarówno do oceny jakości wykonania i montażu jak też do wykrywania uszkodzeń zmęczeniowych przekładni zębatych.

Słowa kluczowe: przekładnie zębate, diagnostyka przekładni, lokalna płaszczyzna przyporu, sygnały niestacjonarne, diagnostyka uszkodzeń, modelowanie przekładni zębatych.

INTRODUCTION

Methods of manufacturing quality acceptance of toothed gears are usually limited to the gear geometry measurement (radial runout tolerance, allowable pitch variation, profile tolerance, tooth alignment tolerance etc.) or quasi static composite action tests, a method of inspection in which the work gear is rolled in tight single or double flank contact with a master gear or paired gear [1]. Additionally gearcase geometry measurements are performed to assure compliance with assumed shafts' position tolerances. As a rule, after gear assembly, sound measurements are made to check if the completed gearbox fit the ISO/AGMA norm limits. This kind of measurement is also commonly used for overall gear quality assessment.

As for now there are no other methods that will allow manufacturer to evaluate the gear quality under normal work. Vibroacoustic methods commonly used for detecting gear faults [2], [3] are usually focused on bearing and teeth faults and are not suitable for this purpose. The proposed method, simple in setup equipment and signal analysis, could fill this gap. In its simplest form it requires only acceleration and trigger signals to be recorded simultaneously. It allows assessing meshing quality of particular teeth pairs in completed gearbox during normal gear exploitation and selection of the worst pinion – gear tooth contact in terms of dynamic overload, the factor that is critical for determining the durability of gear. It is therefore possible to detect and localise manufacturing and assembly errors such as pinion/gear shaft misalignment, misalignment of bearing mountings, pitch error, variable distance error, etc.) and investigate growth of these effects during exploitation.

1. CONCEPT OF THE LOCAL MESHING PLANE

Focusing on the single stage gearbox with z_1 teeth on the pinion and z_2 teeth on the gear wheels we could observe $z_1 \times z_2$ different mesh cycles. The cycle repeats every z_1 revolutions of the gear (and z_2 revolutions of the pinion shafts as well) [4]. Assuming averaged gearbox geometry and rotational frequencies (e.g. 25 Hz for pinion shaft) each teeth pair usually enters contact in no less than 1 or 2 seconds. Commonly used methods of vibroacoustic signal analysis are usually averaging time signals [5]. This process results in losing detailed information about mesh cycles of the particular teeth pairs, data that could be used for assessment of the teeth meshing quality. This leads us to the idea of the observation of the gearbox signal in Cartesian coordinates $z_1 \times z_2$ on the so called local meshing plane [6].

Creation of the Cartesian local plane $z_1 \times z_2$ from the gearbox vibroacoustic (VA) signal requires simultaneous recording of the trigger signal that contains synchronisation impulses every one pinion or gear shaft revolution. Only one shaft trigger signal is required, however for proper initial shaft positioning (i.e. selection of the arbitrary beginning of both shafts' revolution) observation of trigger signals from both shafts is essential. The algorithm for creating local meshing plane from the VA signal is as follows:

- Signal resampling in such a way that every revolution must contain the same number of time samples thus eliminating fluctuations in rotational frequency.
- As the results will be presented on a pinion/gear teeth matrix, number of time samples for each revolution should be divisible by the number of teeth on the trigger shaft.
- Division of the resampled signal into sections of the same length K (in number of time samples) corresponding to the arbitrary times of entering pinion-tooth contact (time equivalence of transverse radial pitch starting with a trigger). This corresponds to period T of one shaft revolution divided by the number of teeth on this shaft gear:

$$T = \frac{1}{f_o z} \qquad (1)$$

where f_o is a shaft rotating frequency and z is the number of teeth on this shaft gear.

Signal sections corresponding to the contacts of consecutive teeth pair (i , j) could then be averaged in time domain to eliminate randomness and load fluctuations in the signal. Resulting matrix could be presented in coordinates $z_1 \times z_2$ generating three dimensional local meshing plane (Fig. 1). This operation could be repeated for consecutive time records allowing for comparison and observations of changes in trends of these fragments of signal.

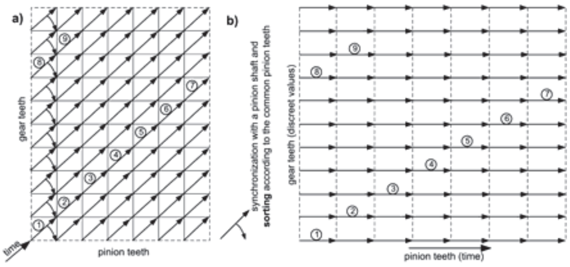

Fig. 1. Construction of local plane for tooth meshing pairs synchronized with a pinion shaft [6]

2. MODEL OF THE GEARBOX

For the purpose of evaluation of the possibility of using local meshing plane method for gearbox quality assessment a model which relied on the method of apparent interference was used [7]. The simplified diagram of the 14 degrees of freedom model is presented on Fig. 2. In the model the mating of toothed wheels is realized by means of a complex flexible element representing meshing. It is assumed that both the gear and the pinion have the possibility of making, without any sliding, an additional rotation in relation to the motion resulting from the revolution of their base circles. Thus the principle of the constant transmission ratio is not maintained enabling analysis of the modulation effects which occur during the toothed gear's operation. This requires modelling of the forces working between the mating teeth to define the relationship between the angular velocities of both toothed wheels. The result of such a wheels motion is the apparent interference (i.e. mutual penetration) of meshing which should be interpreted as the scope of deflection of the teeth in the gear. This interference can be determined by taking into account the meshing geometry and is being compensated by the flexible deformation of teeth.

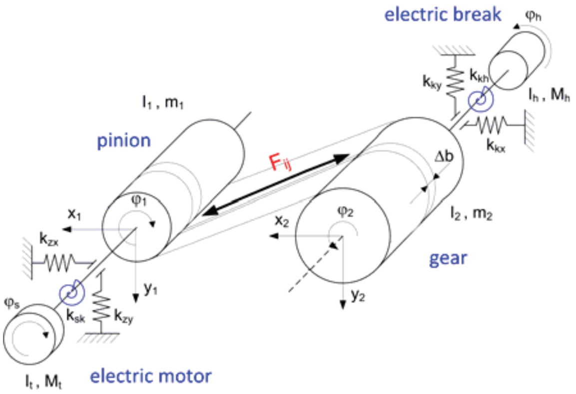

Fig. 2. Diagram of the gearbox model [7]

While calculating the interference of the teeth and the meshing force, a series of factors which influence the geometry of meshing were taken into account:

- variable distance between gear axes resulting from shaft runout or flexible shaft deformation,
- variable radii of addendum circles as well as variable radii of the rounding of tooth tips,
- instantaneous error of standard contact angle,
- pitch errors, variable meshing stiffness along the path of contact etc.

The teeth stiffness and the changes of its value for the entire path of contact were defined by way of a three-dimensional model of a toothed wheel developed with the use of FEM. Although the model allows for helical gear simulations for the results presented in this paper spur gears were selected (z_1=27, z_2=35, m=4, *Load*=850 Nm). High load parameters were selected to allow comparison of the results with back-to-back tester experiments [8].

3. LOCAL MESHING PLANE ANALYSIS OF THE SIMULATED MANUFACTURING ERRORS

A series of simulations were run to evaluate the influence of the manufacturing errors on the gearbox behaviour. The modelled meshing force was selected for this purpose as it is closest to the source of the gear vibrations and is not altered by the signal propagation path, bearings and case stiffness etc. Simulations were run without any other than clearly stated introduced manufacturing errors. All results were pre-processed according to the local plane algorithm described above. In the following analysis squared envelope of the meshing force were used and presented in $z_1 \times z_2$ coordinates as it emphasizes small changes in the signal.

2.1. Simulation of Pitch Errors of gear teeth

Different types of accumulated pitch errors as presented on Fig. 3 were introduced to both gears.

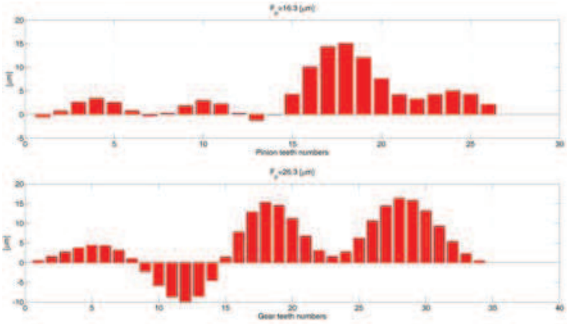

Fig. 3. Simulated accumulated pitch errors of pinion and gear teeth

Additionally some simulations were run with additionally emphasised pitch error introduced on a single pinion and gear teeth. Typical meshing force waveform and it's envelope for one pinion revolution was shown on Fig. 4.

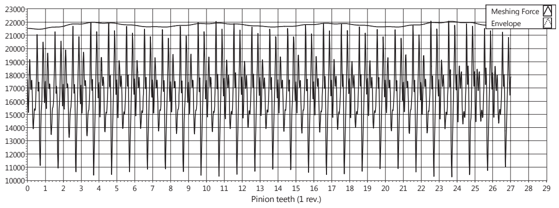

Fig. 4. Meshing force waveform for one pinion revolution

On Fig. 5 maximum values of the squared envelope of meshing force for contacts of all teeth pairs combinations with pitch errors applied as from Fig. 3 were presented in Cartesian "pinion teeth x gear teeth" meshing plane coordinates. Visible are meshing force variations caused by the different pitch errors of pinion and gear teeth and thus the meshing quality in terms of best/worst contact pair of teeth could be determined. If the measured acceleration signal of a gear case would be used instead of simulated meshing force, changes in the accelerations similar to the changes shown on Fig. 5 would be observed reflecting dynamic overload and also allowing for meshing quality assessment.

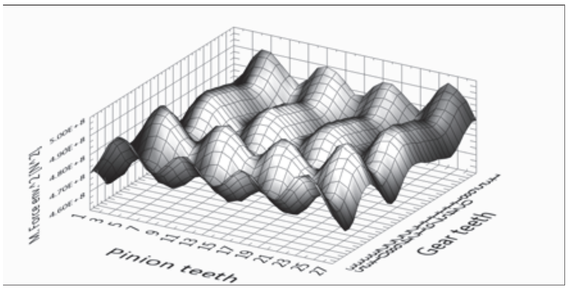

Fig. 5. Local plane analysis of the squared envelope of the meshing force for gears witch pitch errors

Local plane analysis allows for easy selection of particular badly machined teeth or teeth under fatigue degradation. This kind of errors could be introduced into the simulation model as an additional pitch error on one teeth (machining error) or reduced stiffness of the teeth. Fig. 6 presents the simulation results for gears with accumulated pitch errors discussed above but with additionally introduced emphasised pitch errors on single pinion and single gear tooth. These imperfections are introducing periodic deformations into the signal visible on the signal spectrum as a modulations of the meshing frequency with rotational frequencies of both shafts. Observation on the local plane allows for more detailed analysis and selection of the teeth that differ from all others. They are visible as areas of increased amplitudes across one dimension – pinion or gear tooth.

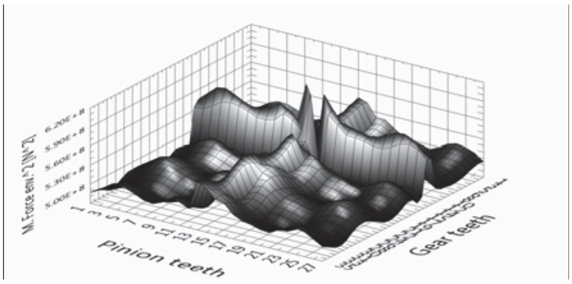

Fig. 6. Local plane analysis of the squared envelope of the meshing force for gears witch additional pitch errors on single pinion and gear teeth

Observation of the maximum values of the signal on the Fig. 6 reveals the same pitch error caused structure as on Fig. 5 but with an addition of characteristic cross pattern caused by contacts of badly manufactured single pinion and gear teeth. In case of the contact of these teeth (centre of diagram) additional excessive signal deformations are visible resulting in additional gear vibrations – additional dynamic overload. This is a typical pattern that will be observed anytime when two deformed teeth will match each other.

2.1. Simulation of Runout Error (F_r) of gear teeth

Runout error defines the runout of the pitch circle. This error, in radial position of the teeth, is most often measured by indicating the position of a pin or ball inserted in each tooth space around the gear. It introduces periodic changes in the signal resulting from the modifications of the shape of the involute, mainly modifications of the radii of the beginning of teeth profiles. As it is impossible to directly model runout error it was alternatively introduced to the model as an error of the base circle.

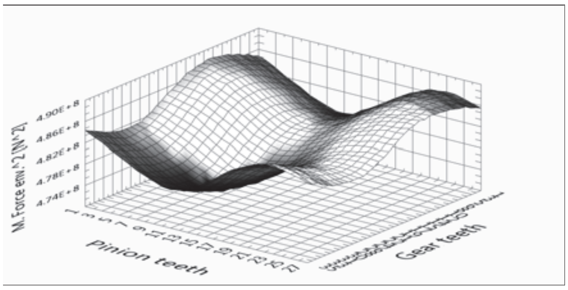

Fig. 7. Local plane analysis of the squared envelope of the meshing force for gears with sinusoidal base circle errors

On the local plane this kind of error with period of shaft rotation on both shafts is visible as a “hat shaped” surface. Results presented on Fig. 7 were obtained assuming sinusoidal base circle errors of less than 40 μm on both gears. The exact shape depends also of the phase shift of the signal caused by the trigger position (see Fig. 8).

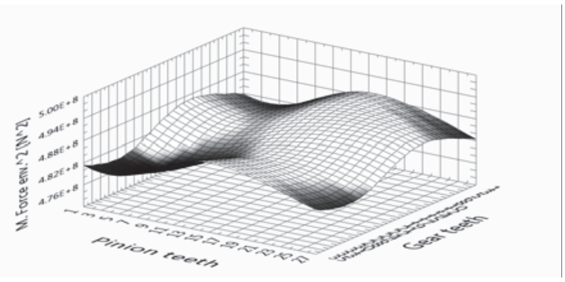

Fig. 8. Local plane analysis of the squared envelope of the meshing force for gears with cosinusoidal base circle errors

3. VERIFICATION OF THE METHOD ON THE GEAR TEST STAND

Application of the local meshing plane method for the control diagnostic of gears was verified on a back-to-back test stand. Test stand was equipped with strain gauges applied to the pinion shaft. Telemetric module allows for recording load changes in this shaft during normal operation. Observation of the load variations on the local plane (Fig. 9) reveals small periodic load changes that could be linked to the gear mounting errors that exists due to the eccentricities and looseness in the gear mounting keyways.

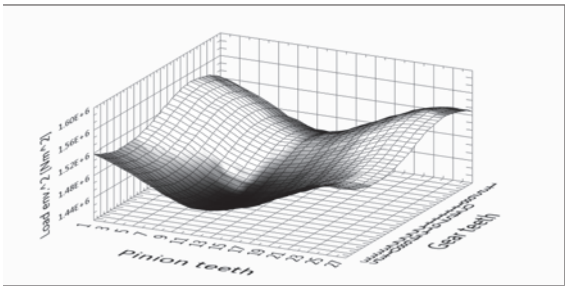

Fig. 9. Local plane analysis of the squared envelope of the pinion shaft load (experiment)

Observation of the gearbox acceleration on the local plane (Fig. 10) for the same gear set reveals increased acceleration level for pinion teeth 14-19 indicating their slightly increased pitch errors.

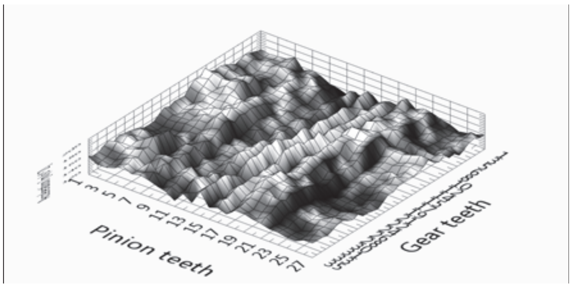

Fig. 10. Local plane analysis of the squared envelope of gearbox accelerations (experiment)

Fig. 11 shows the local plane acceleration signal analysis performed on the same test stand but equipped with different gear set. There is an increased signal level visible for several consecutive pinion teeth (9-13) indicating their manufacturing errors. Some variations of the signal with period of one gear revolution are also visible. This could be linked to the eccentricity of mounting gear wheel.

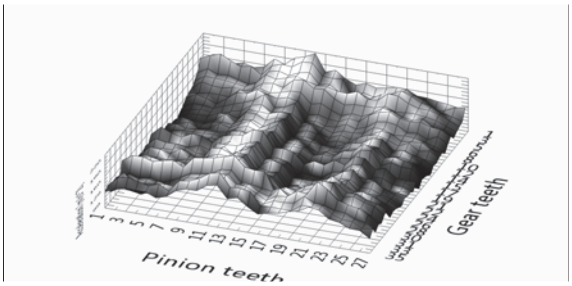

Fig. 11. Local plane analysis of the squared envelope of gearbox accelerations (experiment)

4. SUMMARY

Creation of the local meshing plane should be treated as a type of signal pre-processing. Local meshing plane is simply a new domain of presenting bare or processed signal or even its parameters. Data could be displayed as an easy interpretable three dimensional maps. Each chunk of the signal on this plane has its own physical interpretation as an image of the particular teeth pair contact. It could be averaged over consecutive contacts of the same pair and stored for future trend comparison. Any signal post-processing could then be applied for this time data. In the paper maximal values of squared envelope of the signal were used for this purpose.

Usage of the gear mathematical model allowed for easy introduction of precisely known gear imperfections and observations of the changes in the signals they are producing. As an example of manufacturing errors pitch and runout errors were selected although comparable results will be obtained when analysing other manufacturing errors that are periodic with period related to the shafts revolution (eg. eccentricity, shaft misalignment etc.).

The described method of the local plane can be a useful complement of currently used methods of machinery quality acceptance procedures. Proposed method is noninvasive and requires relatively simple equipment. It allows to investigate an assembled gear working in its natural conditions. It is possible to detect manufacturing and assembly errors (such as: pinion/gear shaft misalignment, misalignment of bearing mountings, pitch error, variable distance error etc.) and investigate growth of these errors during exploitation. Observation on a local “pinion teeth x gear teeth” plane allows observation of tooth contact during normal work and selection the worst pinion – gear tooth contact in terms of dynamic overload, the factor that is critical for determining the durability of gear.

Additionally local plane allows for detecting fatigue damages that occur to the gears during the exploitation [9].

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