Mechanical Systems and Signal Processing 88 (2017) 399–412

Contents lists available at ScienceDirect

Mechanical Systems and Signal Processing

journal homepage: www.elsevier.com/locate/ymssp

A disassembly-free method for evaluation of spiral bevel gear assembly

Lukasz Jedliński*, Józef Jonak

Department of Machine Design and Mechatronics, Lublin University of Technology, ul. Nadbystrzycka 36, 20-618 Lublin, Poland

ARTICLE INFO

Keywords:
Spiral bevel gear
Assembly
Neural network
Helicopter
Control diagnostics

ABSTRACT

The paper presents a novel method for evaluation of assembly of spiral bevel gears. The examination of the approaches to the problem of gear control diagnostics without disassembly has revealed that residual processes in the form of vibrations (or noise) are currently the most suitable to this end. According to the literature, contact pattern is a complex parameter for describing gear position. Therefore, the task is to determine the correlation between contact pattern and gear vibrations. Although the vibration signal contains a great deal of information, it also has a complex spectral structure and contains interferences. For this reason, the proposed method has three variants which determine the effect of preliminary processing of the signal on the results. In Variant 2, stage 1, the vibration signal is subjected to multichannel denoising using a wavelet transform (WT), and in Variant 3 – to a combination of WT and principal component analysis (PCA). This denoising procedure does not occur in Variant 1. Next, we determine the features of the vibration signal in order to focus on information which is crucial regarding the objective of the study. Given the lack of unequivocal premises enabling selection of optimum features, we calculate twenty features, rank them and finally select the appropriate ones using an algorithm. Diagnostic rules were created using artificial neural networks. We investigated the suitability of three network types: multilayer perceptron (MLP), radial basis function (RBF) and support vector machine (SVM).

1. Introduction

Toothed gears are applied more widely than other types of mechanical gears due to their high efficiency and durability, small dimensions and low weight. Particular attention is paid to gears which are either critical for people's safety or whose failure will cause heavy financial losses. Such parts include helicopter gears which are investigated in this study.

The failure-free and long-lasting life of gears strongly depends on their design, production, assembly and operation [1]. The majority of diagnostics-related studies focus on gear operation and fault detection, e.g. [2,3]. The gear assembly process seems to be of lesser interest to researchers even though it is equally crucial. To give an example, if this process is run incorrectly, it can cause premature gear failure and lack of assumed operating parameters. The assembly process for spur gears differs from that for bevel gears. If parts used for the production of spur gears are free from defects, the assembled gears will have the required quality. In bevel gears, however, gear wheels must be assembled individually.

The most important parameters in spiral bevel gear assembly are: mounting distance, contact pattern and backlash [4]. Contact pattern is a complex parameter which takes account of all factors connected with gear assembly. The same cannot be said about

* Corresponding author.
E-mail address: l.jedlinski@pollub.pl (L. Jedliński).

http://dx.doi.org/10.1016/j.ymssp.2016.11.005
Received 19 March 2015; Received in revised form 31 October 2016; Accepted 7 November 2016
Available online 14 November 2016
0888-3270/

backlash; spiral gears can be assembled in various positions with a correct backlash but at incorrect mounting distances. Nonetheless, if spiral gears are set only in compliance with recommended mounting distances, any manufacturing deviations of gear housing or drive shaft can also lead to incorrect assembly.

Vibrations are considered to be the basic source of information about gear condition. Although the vibration signal contains a great deal of information, it is also very complicated and full of interferences at the same time. To increase the signal-to-noise ratio, researchers employ and develop various methods for noise reduction [5–9], including WT. There are numerous publications on the mathematical foundations of this transform and its applications in various fields, including engineering, medicine and chemistry. The use of WT offers a wide spectrum of benefits. Its diagnostic applications mainly include signal visualization [10], denoising [11,12], data compression and decomposition. Vibration signals are usually recorded for more than one channel, which is useful for noise identification and reduction. In this study, we applied a denoising method in multidimensional data using WT [13], which is an extension of the denoising procedure for one-dimensional data.

Following its initial processing, the vibration signal can be directly used to infer about the condition of a tested object. A more common practice is to determine signal features enabling selection of information that is crucial for diagnostics. There is a wide number of features used in diagnostics. These features are determined in time, frequency and time-frequency domains. Some of them are taken from statistics (e.g. kurtosis, standard deviation), while others have been developed specially for the purpose of gears (e.g. FM0, NA4, M6A). The extent of information content of a given feature depends, among others, on the purpose of diagnostics and the object being tested. The features which do not reflect the trend must be rejected because they decrease diagnostics effectiveness. Another shortcoming of using non-optimum features is that it leads to creating an over-developed inference algorithm. Currently, there are two widely used approaches to feature reduction: extraction and selection. The first approach involves the use of more general methods. Here, based on the entire set of features, new features are created by linear or nonlinear transformation. However, the newly created features are not physical, which can make solving the problem difficult. Feature selection enables selecting optimum features available. The method for feature selection employed in the present study is based on thresholding to enable the ranking of features and selection of the best ones. One advantage of this approach is that we can use any inference algorithm (in contrast to other types of methods for feature selection, e.g. wrapper approach, embedded methods). In addition, this approach provides vital information.

The determination of diagnostic rules is not an easy task, particularly when nonlinear relationships are involved. This problem can be regarded as identification of a nonlinear model based on input and output signals. Problems of this type can be effectively solved using artificial neural networks [14,15]. We selected MLP, RBF and SVM networks as inference algorithms. The aim of using several neural models is to determine which network is most suitable to solve the problem in question. The MLP network is a well-known and effective algorithm for solving diagnostic problems. The RBF network is more recent than the MLP and – as some authors claim [16] – is more effective. Nonetheless, the difficulty which can arise in the learning of the MLP and RBF networks is that the learning process may stop in a local minimum. This results from the operation of algorithm learning. This difficulty does not occur in the SVM, which is a popular method developed in its current form in the 1999s.

Experimental tests are the main source of information when investigating new problems, particularly complex ones. In addition, experimental results and findings are less controversial. Numerical simulation methods are based on or verified by empirical results. Numerical results and findings cannot, however, always be easily applied in practice, which results from inevitable simplification of numerical models and the fact that they do not take into account disturbances occurring in real conditions. For this reason, the method proposed in this study is developed and verified experimentally, with tests performed on a test stand.

Taking the above into consideration, we propose a novel disassembly-free method for evaluation of the quality of spiral bevel gear assembly. The fundamental assumption of this method is that there is a relationship between gear wheels position and vibration signal. Given the causal connection between the assembly and vibration activity of gears, it is therefore possible to develop a method which will enable examination of gear position in a finished product. This method can be an objective and automatic way of assembly control.

2. Test-stand investigation of bevel gears

2.1. Tested gears

The investigation concerned the assembly of thirteen new tail rotor gears. These single-stage spiral bevel gears have a 90° angle between the axes. The pinion has 19 teeth, while the wheel has 42 teeth.

The pinion and gear shaft are supported in rolling bearings. The mounting distances between the gears can be adjusted by the application of different thickness shims. Fig. 1 shows the schematic design of this gear. Additional information about this type of gearbox with respect to contact pattern and spectra can be found in [3,17].

2.2. Test stand

The test stand was powered by an electric motor. Given the high angular velocity of the tested gear, it was necessary to use a multiplier with spur gears. Load torque was applied by a water brake and verified using a torque transducer (Fig. 2).

The test stand was used to control and calculate vibrations, temperature, load torque and the angular velocity of gears. Vibrations were measured using two three-axis acceleration sensors, Brüel & Kjaer type 4321, equipped with B & K Nexus signal conditioners as well as the National Instruments PXI-1044 measurement PC provided with the NI PXI-4472B measuring card and LabView