Nationaal Lucht- en Ruimtevaartlaboratorium

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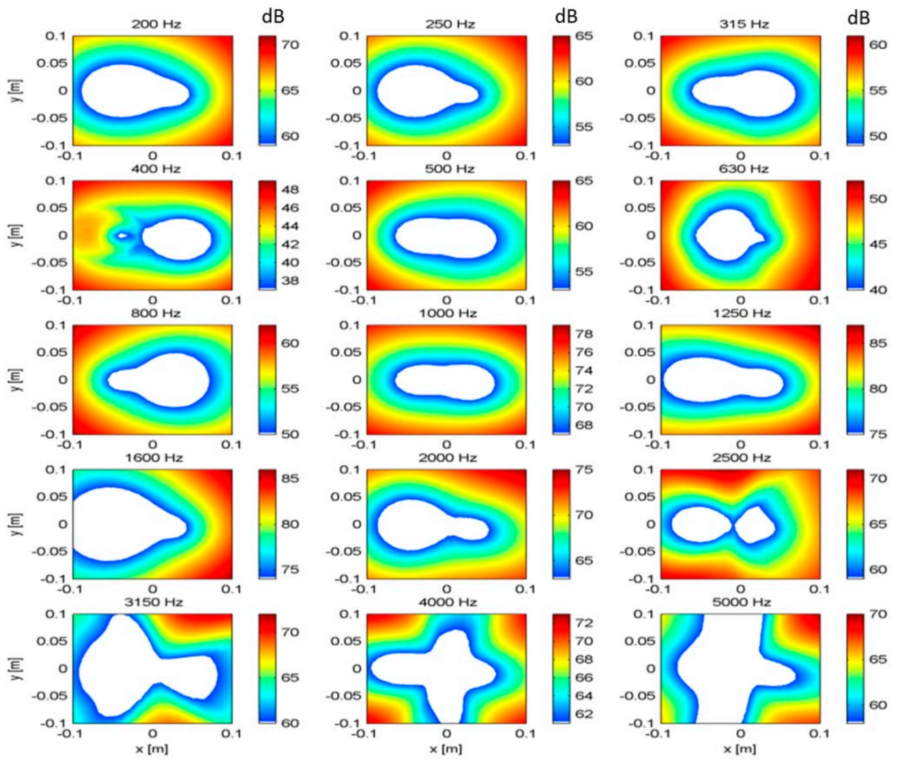
Executive summary

Acoustics-Based Seeded Rotary Gear Fault Detection

The Use of an Internally Mounted Acoustic Antenna Array and The Assessment of Condition Indicators



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Knowledge area(s)
Levensduurbewaking en onderhoud van vliegtuigen

Descriptor(s)
Drive Train
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Condition Based Maintenance (cbm)
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Problem area
The Dutch Ministry of Defence funded a research project called "HeliHUMS" exploring the possibility of improving drive train condition monitoring by means of an innovative acoustic method. Acoustic antennas have become in use as standard tools for acoustic source location. Advantages of such arrays are the spatial isolation of the target source from spurious sources and the gain in signal-to-noise ratio. Furthermore, microphone arrays offer the opportunity to locate sources on moving objects, individual gear teeth in this application. Question arose whether acoustic-based condition monitoring could attain similar or improved sensitivity to the changes

This report is based on a presentation held at The 1st International Conference on Advances in Structural Health Management and Composite Structures (ASHMCS), Jeonju, South-Korea, 29-31 August 2012.

of gear box health as vibration-based condition monitoring.

Description of work
This report contains two publications (Part 1 and 2) on the results from the acoustic-based seeded fault detection in a rotary gear box. Part 1 of the paper presents results from the feasibility study of an acoustic antenna for gearbox health monitoring. Part 2 of the paper presents results from the assessment of condition indicators and cepstrum analysis for gear box health monitoring.

Acoustic array measurements with perfect and seeded fault (removal of part of one tooth, see Figure 1C, Part 1) gears were performed under different load conditions and rotation speeds. The acoustic data were processed assuming on steady (area of mating gear teeth) and moving source locations (individual rotating teeth).

Based on the measurements from Part 1, 16 acoustic condition indicators were calculated (see Table 1, Part 2). In addition, cepstrum analysis was performed on the same measurements.

Results and conclusions
The acoustic source maps did not reveal dominant sources at the location of the mating gear teeth (see Figure 3, Part 1). The assessment has shown that RMSD, RMSR, FM4, M6A and M8A methods were found to be suitable as acoustic condition indicators for their sensitivity to gear tooth damage while being independent to rotation speed and applied load (see Figure 2, Part 2). Furthermore, the cepstrum analysis has revealed that the main quefrency component attenuates when a gear tooth was removed to simulate the damage (see Figure 3, Part 2).

Applicability
HUMS, drive-train health monitoring, condition-based maintenance.

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Acoustics-Based Seeded Rotary Gear Fault Detection

The Use of an Internally Mounted Acoustic Antenna Array and The Assessment of Condition Indicators

J.S. Hwang and E.R. Rademaker

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Summary

The Dutch Ministry of Defence funded a research project called “HeliHUMS” exploring the possibility of improving drive train condition monitoring by means of an innovative acoustic method. This report contains two publications (Part 1 and 2) on the results from the acoustic-based seeded fault detection in a rotary gear box. These papers will be presented at The 1st International Conference on Advances in Structural Health Management and Composite Structures (ASHMCS), which will be held at Jeonju, South-Korea, between 29th and 31st of August, 2012.

Part 1 of the paper presents results from the feasibility study of an acoustic antenna for gearbox health monitoring. Acoustic antennas have become in use as standard tools for acoustic source location. Advantages of such arrays are the spatial isolation of the target source from spurious sources and the gain in signal-to-noise ratio. Furthermore, microphone arrays offer the opportunity to locate sources on moving objects, individual gear teeth in this application. Acoustic array measurements with perfect and seeded fault (removal of part of one tooth, see Figure 1C, Part 1) gears were performed under different load conditions and rotation speeds. The acoustic data were processed assuming on steady (area of mating gear teeth) and moving source locations (individual rotating teeth). The acoustic source maps did not reveal dominant sources at the location of the mating gear teeth (see Figure 3, Part 1).

Part 2 of the paper presents results from the assessment of condition indicators and cepstrum analysis for gear box health monitoring. Question arose whether acoustic-based condition monitoring could attain similar or improved sensitivity to the changes of gear box health as vibration-based condition monitoring. Based on the measurements from Part 1, 16 acoustic condition indicators were calculated (see Table 1, Part 2). In addition, cepstrum analysis was performed on the same measurements. The assessment has shown that RMSD, RMSR, FM4, M6A and M8A methods were found to be suitable as acoustic condition indicators for their sensitivity to gear tooth damage while being independent to rotation speed and applied load (see Figure 2, Part 2). Furthermore, the cepstrum analysis has revealed that the main quefrency component attenuates when a gear tooth was removed to simulate the damage (see Figure 3, Part 2).

Contents

ACOUSTICS-BASED ROTARY GEAR FAULT DETECTION: PART I THE USE OF AN INTERNALLY MOUNTED ACOUSTIC ANTENNA ARRAY

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ABSTRACT

The Dutch Ministry of Defence funded a research project on acoustics-based health monitoring. Part 1 of the paper presents results from the feasibility study of an acoustic antenna for gearbox health monitoring. Acoustic antennas have become in use as standard tools for acoustic source location. Advantages of such arrays are the spatial isolation of the target source from spurious sources and the gain in signal-to-noise ratio. Furthermore, microphone arrays offer the opportunity to locate sources on moving objects, individual gear teeth in this application. Acoustic array measurements with perfect and seeded fault (removal of part of one tooth) gears were performed under different load conditions and rotation speeds. The acoustic data were processed assuming on steady (area of mating gear teeth) and moving source locations (individual rotating teeth). The acoustic source maps did not reveal dominant sources at the location of the mating gear teeth.

Keywords: Drive train, Acoustic antenna, Acoustic array, Gear box

1. INTRODUCTION

Helicopter drive train elements such as bearings, gear teeth and drive shafts are subjected to deterioration under loaded conditions during normal operation. Gear box elements mainly deteriorate due to gear tooth contact dynamics. The accumulated damage can manifest itself in a variety of forms, including pitting, scoring, spalling and incipient cracks. These damages affect system performance and may ultimately lead to failure. Numerous researchers have attempted to develop qualitative and quantitative fault detection methods using vibration measurements with accelerometers, which interpretation is complicated by coupled structure-borne effects. Fortunately, gear box faults also appear via acoustic paths as a result of tooth by tooth contact that occurs during meshing. Hence, sound radiating from gear contact may represent an alternative method for detecting incipient failure modes of individual teeth. A feasibility study on the use of acoustic antenna's placed in the open (far)-field of mating gear wheels has been carried out by [1]. The objective of this experiment is to diagnose the health of two mating gear wheels with an acoustic antenna installed within a closed gear box.

2. TEST SET-UP AND TEST PROGRAM

The spur gear test rig is an existing closed box reduction gear. It consists of a 400 V DC electro-driver with a maximum power of 8 kW. The closed gear box consists of two gear wheels: a driver wheel with 25 teeth (perfect and seeded fault) and a driven wheel with 45 teeth. Tooth width is 2 mm. The shaft speed can be electronically varied between 10 and 3500 rpm. The output axis is connected with a mechanical disc brake, which is manually and hydraulically (cantilever) operated to simulate loaded conditions. Note that no torque meter is applied to measure the dissipated mechanical energy. A laser-tachometer is used to obtain the 1-p signal used in the processing. Two openings in the gear box housing have been milled to facilitate the mounting of the acoustic array, consisting of two probes of 5 microphones each (Panasonic Electret WM-61A). Two alternative array placements were investigated with 10 microphones above (Fig. 1a) and 5 microphones in front of the two mating gear wheels (Fig. 1b). The array post-processing software is the same as developed for use in the wind tunnel DNW-LLF [2].

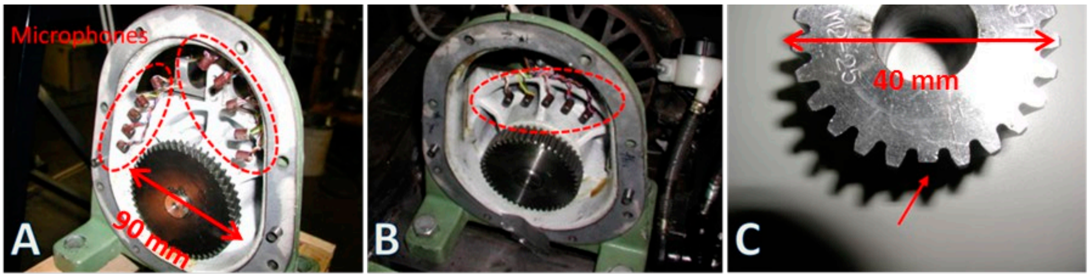

Fig. 1 Two alternative array placements: two microphone probes above mating gears (A); one microphone probe in front of mating gears (B); driver seeded fault gear wheel (C) placed on top of large driven gear wheel (A and B)

The test program consists of acoustic array measurements at 12 driver shaft speeds varying between 250 and 3000 rpm with an increment of 250 rpm (Table 1). The gear is operated with perfect and seeded fault driven gear wheel for unloaded and loaded (with employed brake) conditions.

Table 1. Test program seeded fault spur test rig.

	Shaft speed: 250 (250) 3000 rpm	
Perfect gear	Unloaded	Loaded
Damaged gear	Unloaded	Loaded

3. RESULTS

Microphone (phase-locked) order spectra at the highest shaft speed (3000 rpm) for the perfect and damaged gears show spectral levels between 25 and 95 dB (Fig. 2). Maximum levels for the perfect gear wheel occur at twice the meshing frequency, for the damaged gear in the range between the meshing frequency (1250 Hz) and its harmonic.

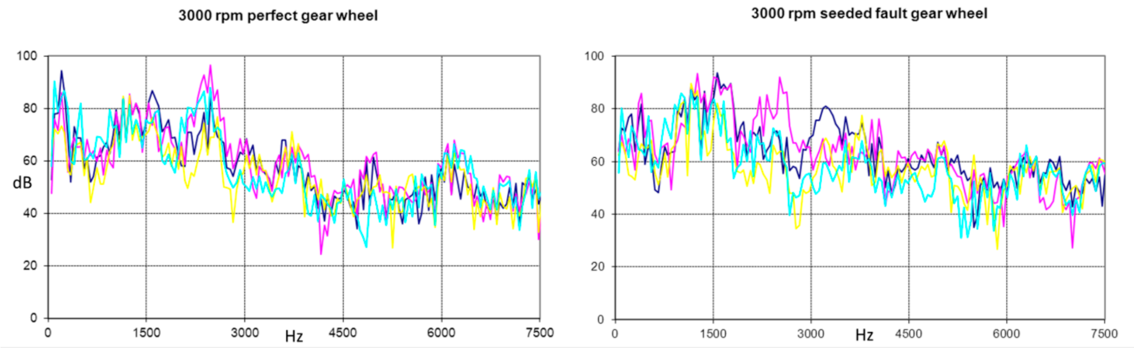

Fig. 2 Microphone order spectra of loaded gear, 3000 rpm, perfect (left) and damaged (right) gears

These spectra are used in the array processing software to produce acoustic source maps, for which a typical example is shown in figure 3 (3000 rpm, loaded configuration and damaged gear). It occurs that the acoustic source map is fully dominated by spurious sources, whereas no clear source is found at the location of the mating gear wheels. This triggered other acoustic analysis on the microphone data described in the joint paper [3].

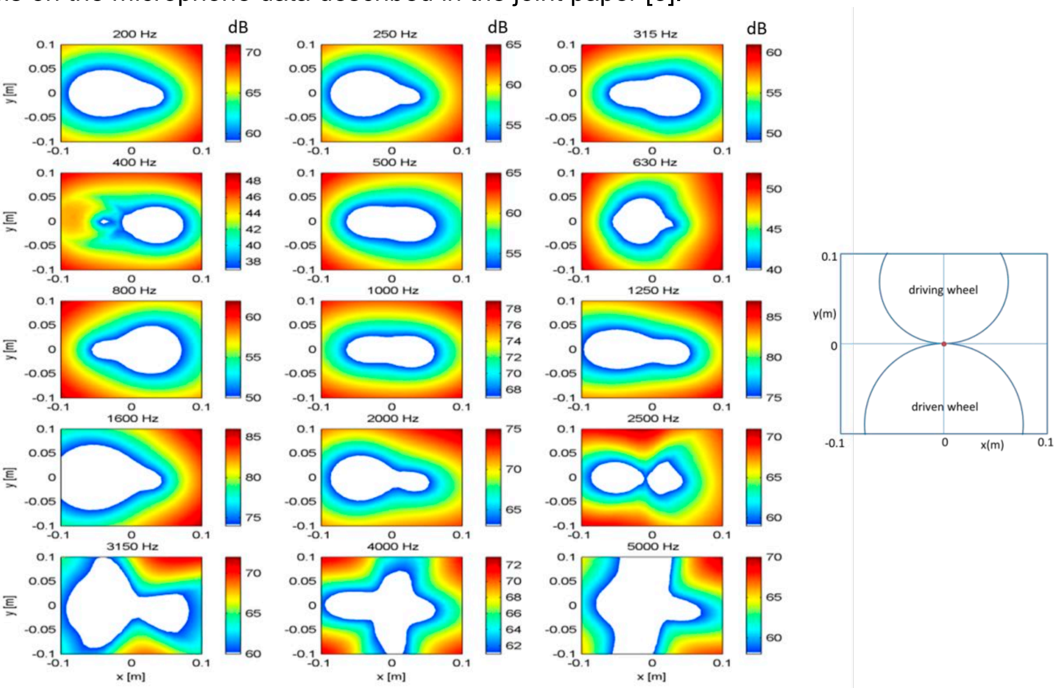

Fig. 3 Acoustic source map of the mating gear wheels (located at center of plots), 1 microphone probe in front of the gear wheels, loaded damaged gear, driver shaft speed 3000 rpm, mesh frequency 1250 Hz

4. CONCLUSIONS AND RECOMMENDATIONS

A feasibility experiment with an acoustic antenna on a seeded fault spur gear test rig has been carried out to evaluate helicopter drive train monitoring and damage detection by listening. An existing closed reduction spur gear test rig with two gear wheels (driver and driven wheel with 25 and 45 teeth at a maximum transmitted power of 8 kW) has been modified to a configuration to facilitate the instrumentation with a phased array. Tests were carried out at various shaft speeds in the range between 250 and 3000 rpm for loaded and unloaded conditions with perfect and damaged (seeded fault) driver gear wheel. The following conclusions from the seeded fault gear box test are drawn:

1. An acoustic antenna placed inside the gear box housing does not give much additional value compared to a single microphone. The source map plots do not reveal any acoustic sources at the location of the mating gear teeth. The source maps are dominated by other spurious sources in the gear box housing.
2. The acoustic environment in the gear box housing is too complex for an adequate application of the acoustic antenna. The acoustic field is strongly reactive and the distances between the antenna and the source are too small. Moreover, the number of microphones compared to the normal application of aero-acoustics antennas is very low.
3. The use of a single acoustic signal has some potential to discriminate between healthy and damaged gears. A striking difference observed between the perfect and damaged gears was the presence and absence of distinct mesh frequencies and harmonics at low shaft speeds respectively. This was also confirmed by the cepstrum analysis (see part 2 [3]).

It is recommended to explore the measured acoustic database further with combined time-frequency analysis techniques and judge these on their merits for acoustics based condition monitoring.

ACKNOWLEDGEMENT

The authors would like to acknowledge the support and funding of the Defence Materiel Organisation (DMO) of the Ministry of Defence in The Netherlands.

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ACOUSTICS-BASED ROTARY GEAR FAULT DETECTION: PART II ASSESSMENT OF CONDITION INDICATORS AND CEPSTRUM ANALYSIS

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ABSTRACT

The Dutch Ministry of Defence funded a research project on acoustics-based health monitoring. Part 2 of the paper presents results from the assessment of condition indicators and cepstrum analysis for gear box health monitoring. Question arose whether acoustic-based condition monitoring could attain similar or improved sensitivity to the changes of gear box health as vibration-based condition monitoring. Based on the measurements from Part 1, 16 acoustic condition indicators were calculated. In addition, cepstrum analysis was performed on the same measurements. The assessment has shown that RMSD, RMSR, FM4, M6A and M8A methods were found to be suitable as acoustic condition indicators for their sensitivity to gear tooth damage while being independent to rotation speed and applied load. Furthermore, the cepstrum analysis has revealed that the main quefrency component attenuates when a gear tooth was removed to simulate the damage.

Keywords: Health monitoring, Drive train, Condition indicators, Cepstrum analysis.

1. INTRODUCTION

The Dutch Ministry of Defence funded a research project called “HeliHUMS” exploring the possibility of improving drive train condition monitoring by means of an innovative acoustic method. For this purpose, an experimental investigation was carried out at NLR employing an acoustic antenna, fitted to a spur gear test rig to monitor seeded faults. Part 1 of this paper described how phased microphone array was employed in an attempt to detect and locate seeded fault in the gear box [1]. This paper presents means to employ gear box health monitoring utilizing the measurements from Part 1.

A typical condition monitoring system based on vibration measurements is comparing the Condition Indicators (CI’s) of healthy and defected system. The gear box condition monitoring typically calculates the power of few selected frequency components [2, 3]. Furthermore, cepstrum analysis has proven to be an effective way to monitor the health of a gear box [4]. A feasibility study of CI's for acoustic condition monitoring has been conducted.

2. CONDITION INDICATORS

In the helicopter drive train monitoring domain, a large number of CI's can be defined, based on signals acquired with accelerometers. General CI's for gearbox used in this study are enumerated in Table 1. Detailed overviews of these indicators are given in [2].

Table. 1. List of CI's.

CI's:	*Brief description:*
RMS	The square root of the average of the sum of the squares of the signal samples [Pa].
RMSD	RMS for the difference signal [Pa].
RMSR	RMS for the residual signal [Pa].
CF	Crest factor [-].
ER	Amplitude ratio of RMSD and RMSYD [-].
FM0	The ratio of the signals peak-to-peak value and the RMS of RMSYR [-].
FM1	Amplitude ratio of the RMS value of the contributions of the 1^{st} and 2^{nd} order side bands of the mesh frequency and RMSYR [-].
FM4	Kurtosis of the difference signal [-].
M6A	6^{th} statistical moment of the difference signal [-].
M8A	8^{th} statistical moment of the difference signal [-].
SP1	RMS value of the mesh frequency [Pa].
SP2	RMS value of the first harmonic of the mesh frequency [Pa].
SP3	RMS value of the second harmonic of the mesh freq. [Pa].
SLF	Ratio of the RMS of the summation of 1^{st} order side bands and the RMS of the summation of mesh frequencies and harmonics [-].
RMSYD	RMS for signal containing only mesh frequencies, harmonics and 1^{st} order side bands [Pa].
RMSYR	RMS for signal containing only mesh frequencies and harmonics [Pa].

The acoustic data are acquired from four microphones at four test conditions and 12 shaft speeds, see Part 1 [1]. A tacho-signal of the driving gear was simultaneously measured to be able to apply the phase-locked time-domain averaging technique. Furthermore, the data were resampled to obtain a sample number equal to 2^m, which allows the use of Fast Fourier Transform (*m* as an integer). At the same time, the DC-value of the signals has been removed.

3. CEPSTRUM ANALYSIS

In addition to the CI's, a cepstrum analysis has been performed on the seeded fault gear box test. The power cepstrum was determined on the phase-locked time-domain averaged signal. The test conditions were defined in the same manner as for the CI's, see Table 2.

4. RESULTS

Figure 1 presents the normalized mean values and Standard Deviations (SD) of the CI's.

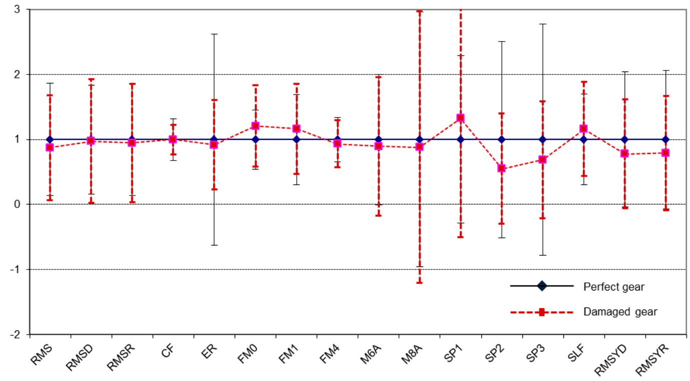

Figure 1. Normalized CI's (perfect gear is set to 1) with the SD of the perfect and damaged gears.

Figure 1 shows that the spreading of the calculated CI's is larger than the difference in its mean values. In order to determine dependency of the CI's on the rotational speed and applied load, the relative difference in CI's was calculated between the perfect and damaged gears with speed as variable. Results were linearized with the least-squares method. Figure 2 shows a result of measurements from microphone 3. Ideal CI's should have a flat slope (independent to the rotational speed), both in loaded and unloaded cases (independent to the external load).

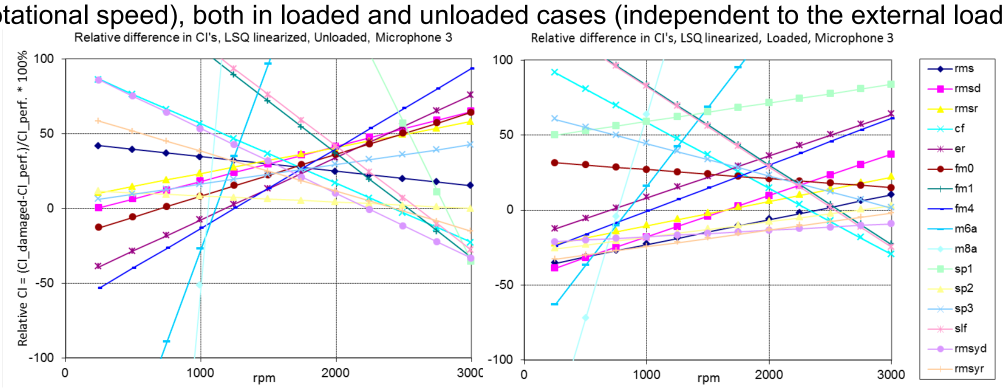

Figure 2. The effect of gear condition as a function of shaft speed for the unloaded and loaded gears.

Figure 3 shows a power cepstrum of the acoustic signal from microphone 2 as an example. The rotational speed was 250 rpm, driving wheel had 25 teeth, and measurement speed was 50kHz, which means that the main quefrency component can be expected around 481 [4]. This example shows that this component attenuates when damage was present. However, further cepstrum analysis showed that the amount of attenuation strongly depends on the rotational speed.

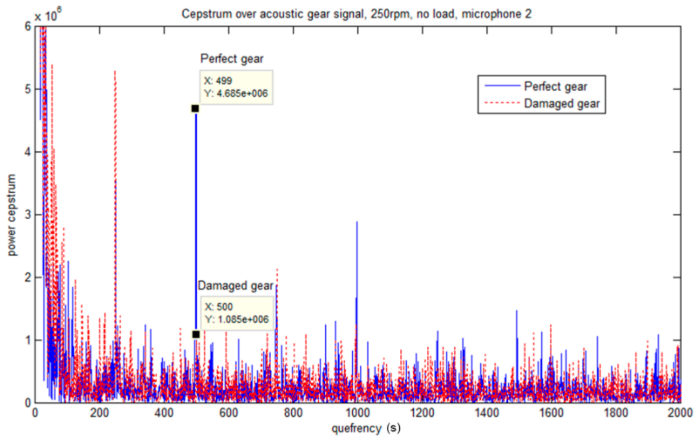

Figure 3. Power cepstrum of the undamaged and damaged gear box, speed = 250 rpm, unloaded.

5. CONCLUSION AND RECOMMENDATIONS

It can be concluded from Figure 1 that the mean CI difference between perfect and damaged gear is relatively small, except for few CI's (ex. SP1, SP2). Moreover, the standard deviations are larger than the difference in mean value. Further study has shown that RMSD, RMSR, FM4, M6A and M8A are potential suitable acoustic CI's. Figure 2 shows that these indicators have a weak dependency on gear loading and a strong and consistent dependency on gear condition. The main quefrency component attenuates when a gear tooth was removed, depending on the rotational speed of the gear box. The strong presence of noise in the gear housing causes that this feature is hard to detect with acoustic measurement. Overall, acoustic based gear health monitoring does not outperform vibration based methods.

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The authors would like to acknowledge the support and funding of the Defence Materiel Organisation (DMO) of the Ministry of Defence in The Netherlands.

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