# Dynamic Modeling and Sound (Noise) Diagnostics of Robot Gearboxes for Fault Assessments

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## ABSTRACT

Some gear faults in industrial robots can during operation be recognized as abnormal noise peaks coming from the gearbox. A library of such recordings has been assembled in order to automate fault diagnosis of the robots. A computer records sound from the gearbox and compare the new recordings with recordings stored in the library. The result of the comparison is a diagnosis of the condition of the robot. This paper proposes an extension of the sound library by incorporating model based reasoning. A dynamic model of the gearbox in the drive system has been constructed and gear vibrations on the force level are extracted from the model. These vibrations are projected onto the sound recordings with a statistical vibration diagnostic parameter known as the Crest Factor (CF).

## Introduction

A case-based prototype system that makes a diagnosis based on recordings of noise from an industrial robot noise has previously been implemented [1]. The prototype system analyzes the recordings using Fast Fourier Transform (FFT) [2] for feature extraction and case-based reasoning [3] to make a diagnosis of the condition of the gearbox of the robot.

Gearbox dynamics has often a strong impact on the performance of the system vibrations. In this paper we use Modelica .Mechanics.Rotational Library [5] to simulate gearbox torques, especially for output shaft with applied payload and then compare with noise recordings from a normal and two faulty gearboxes. It is both difficult to simulate gearbox effects and to get reasonable agreement between measurement and dynamic simulation. The gearbox model is created in Dymola and is characterized by tooth contact stiffness, backlash and efficiency. The model has a correct representation of the relation between force and vibration. Several parameters can be altered in order to produce different simulation results. The results of the simulation represent an oscillation of torque on the input and output shaft of the gearbox model.

The simulation results and noise recordings are represented by means of the Crest Factor (CF) [4]. CF is defined as the maximum value of a signal normalized by the RMS value. CF aids the comparative study between noise measurements of normal and faulty gearboxes as well as providing a mean to compare these noise measurements against the simulation results measured on the input and output shaft of the model.

In the majority of cases the regular vibrations and noise effects in the gear sets have been predicted theoretically as well as experimentally by measurements. The theoretical description of the gear noise phenomena has been based mainly on force analysis of multibody models undergoing non-linear tooth and bearing contact conditions, inertia masses and the influences of applied excitation torques. Those directions are highly complicated and involve problem identification, a mathematical formulation and numerical methods. To reduce the gearbox simulation problem to its simplest form we can use modern software e.g. the Dymola tools and Modelica Mechanical Library [5,6].

## Sources of Gear Noise

An ideal gearbox with rigid equally spaced gears, accurate teeth and good lubrication would transmit minimal noise and vibrations. All kinds of deviations from this ideal gearbox cause an increase in vibrations and noise. In the majority of cases the source of noise and vibrations is transmission errors introduced during manufacture. These errors can e.g. be geometry inaccuracies and eccentricities which both results in impact noises [7]. Other sources of impact noises can be gear rattle. Gear rattle is caused by a combination of backlash and

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unloaded gears. Friction and pitting due to gear fatigue is also a source of noise [8].

Most modern techniques for gear diagnostics are based on the vibration signal picked up by an accelerometer from the gearbox casing. The vibration signal is normally filtered by time synchronous averaging (TSA) and analysed in the frequency domain with methods such as the Wavelet Transform (WT) or the FFT. A similar approach is to use a microphone instead of an accelerometer and record the noise from the gearbox. This method was used to detect faults in industrial robots [1] and further work on noise recordings is also presented in this paper.
The expected noise spectrum from a gearbox should contain the gear meshing frequencies and integer multiples of it. There is also common with harmonics and sidebands due to gear eccentricities and geometric errors. Figure 1 shows a FFT of the recorded noise of an industrial robot.

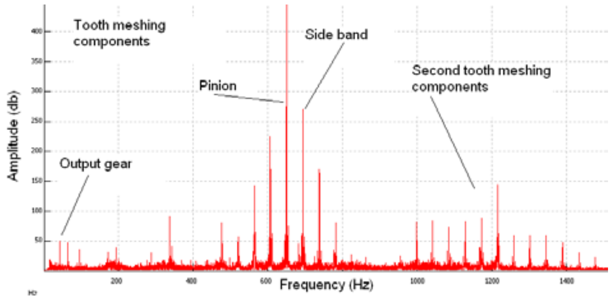

Figure 1 FFT spectrum of gear noise analysis.

The recordings are first pre-processed in order to remove unwanted noise. In this case the recordings are filtered with a low pass filter that removes all noise above 200 Hz. The result contains the most important meshing frequencies which localizes the amplitude increments during a rotation period. These amplitude increments arise from the transient force effects introduced by the cracked tooth in the driven gear wheel.

## Simulation of Drive Model in Dymola / Modelica

A dynamical model can take a look how typical design of multi-body system is done with an emphasis in our target on the Dymola tools and Modelica Library [5,6]. The Modelica Mechanical Rotational package components was developed for the fundamental units of a mechanical system like inertia, gear, gear efficiency, friction in bearings, clutches, brakes, external torques, backlash, cut of torque of a flange and others. Every basic mechanical component from the Modelica Library has at least one interface to connect the element rigidly to other mechanical elements. The underlying feature of this library is the component-oriented modeling is based on the solution of mixed continuous/discrete systems of equations or DAEs equations.
A drive train dynamical model of robotics arm system is shown on Figure 2 as structural modal and on Figure 3 is represented composition diagram of a sample system build in Dymola environment and Modelica icons. It is a composite model which specifies the topology of the system to be modeled in terms of components and connections between the components.
The following setup parameters and assumptions are applied to model simulation: $I_1 = 0{,}6kgm^2$ is a motor inertia (pos.3 on diagram) which is driven by a sine-wave motor torque $T_1$ (pos.1 and 2 on fig.3) The torque sinusoidal signal is provided by values: torque amplitude $T_a = 12Nm$ and simulation (case-study) frequency $fr = (0{,}4;0{,}5)$ Hz (rps). These frequencies are obtained from real time rotation period of robot arm payload $\tau = 2 - 2{,}2\sec$ . Via a gearbox (pos.4) the rotational energy is transmitted to load inertia $I_2$ (pos.5). For simulation purpose we used following variable cases of load inertia:
$I_2 = 20;40;50\ kgm^2$ .

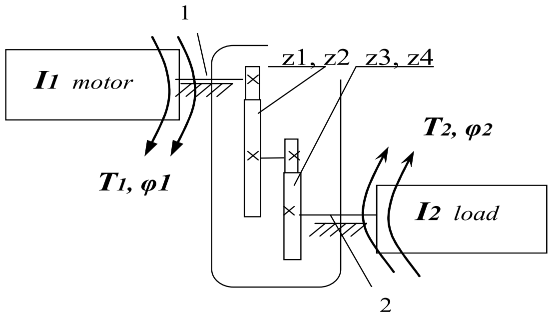

Figure 2 Dynamical model of gearbox drive.

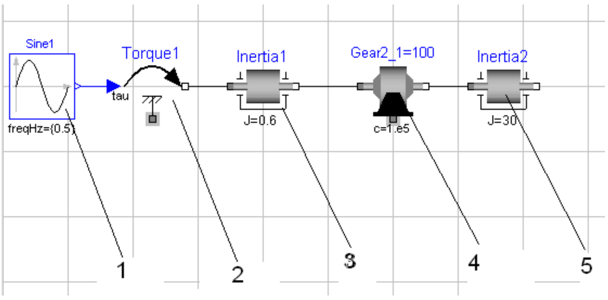

Figure 3 Composition diagram of gearbox drive in Dymola/Modelica.

The library gearbox model specified by statement *Gear2_i=100* (Figure 3 ) is a component assembly model of several components taking into account the essential effects of gear vibration and noise leading to different faults between gears teeth . In particular: component *lossyGear* define gear efficiency due to friction between teeth and bearing friction; component *elastoBacklash* – gear elasticity, damping, backlash.

For simulation purposes we use gearbox parameters: I=100 – transmission ration; array of mesh efficiencies 0,9 and bearing friction 0,9. Gear elasticity c=1.e5 (Nm/rad), total backlash b=0 (rad). Simulate and plot for 30 second  the behavior of internal torques on driven shaft by variable *Inertia2 flangea_tau*  and then applied CF formula for obtained data. All calculation results are prepared in table 1. and one case of simulation is shown on Figure 4.

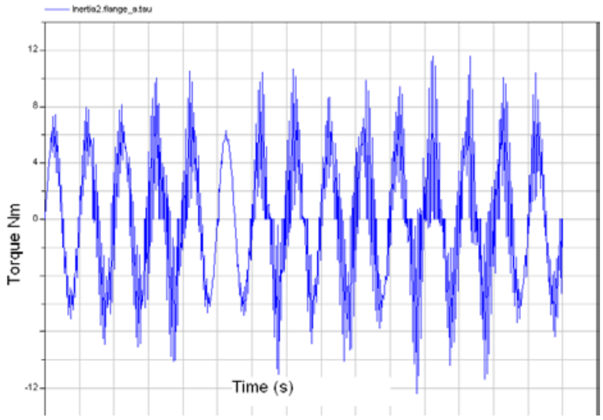

**Figure 4 Torque on driven gearbox shaft. Time history. Fr=0,5 Hz; J2=30 kgm2.**

## Noise Experimental Setup

The gearbox of an industrial robot was used to perform the testing. The robot was mounted in a test cage and a microphone was attached to the gear housing of the axis.

The tested gearbox consists of a common drive train. The drive train has two helical gears driven by a pinion gear that is mounted on the shaft of an electrical motor. The output gear is directly mounted on the robot axis. The gear ratio of the gearbox is 100. It means that one revolution on the output gear corresponds to 100 revolutions on the pinion gear.

The test gearbox is protected by a housing on which a microphone was attached. The location of the microphone was selected in order to get it as close to the gear drive train as possible. A magnet was used to attach the microphone. The microphone is of a common capacitor type and was connected to the sound card of a computer. The sampling frequency was 8 kHz.

## Recording of Noise

The axis was run back and forward with a driver pinion speed of 270 rad/s during the recordings resulting and in an output (driven) shaft speed of about 2.7 rad/s. The recorded unfiltered sound is shown in Figure 5.

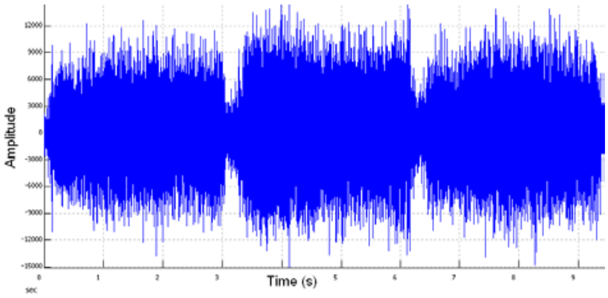

**Figure 5 Unfiltered noise.**

The figure shows three periods of rotations of the output axis. The rotational speed of the output axis is 2.7 rad/s. Two types of faults were observed and recorded with the procedure described above. The sources of the faults were:

1. A notch on the output gear
2. Play between the transfer gear and the output gear

The noise signal from the gearbox needs to be preprocessed in order to extract information about the condition of a specific gear wheel. As can be seen in fig. 1 the meshing frequency of the output gear is below 200 Hz and thus all frequencies above 200 Hz was removed by a low pass filter leaving only frequencies from 0-200 Hz in order to reveal the impulse peaks from the noisy sound recordings. A filtered recording of a fault caused by a notch on the driven gear is shown in Figure 6.

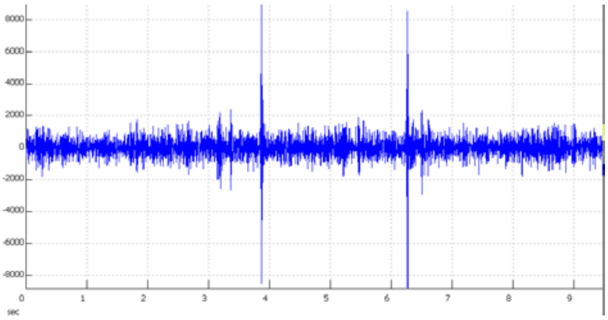

**Figure 6 Filtered sound with notch fault.**

The peaks at time 3.9 and 6.3 seconds in Figure 6 is the result of a small notch on the output gear. The notch is only visible in one direction of rotation and thus leaves the two surrounding periods uninfluenced. The notch is repeated every full rotation of the gear with the same frequency as the rotation speed of the gear.

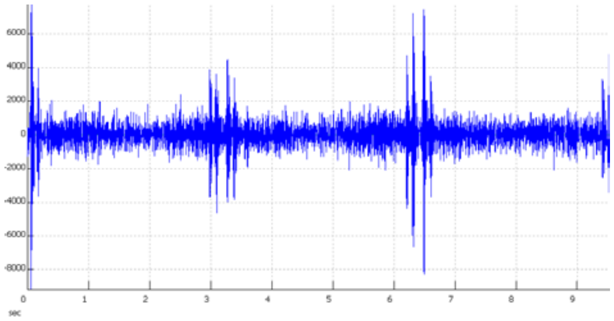

**Figure 7 Filtered noise with play fault.**

In Figure 7 there are peaks visible in the end and the beginning of each rotation of the gear. These peaks are the results of play between the transfer gear and the output gear. At the end of each rotation the force between the transfer gear and the output gear is radically increased causing a backlash with a resulting impulse noise.

## Crest Factor and Results Comparison

In order to make a comparison between the previously explained simulation results and the obtained sound recordings CF was introduced and calculated for each recorded fault and for each simulated fault.

CF is based on the Root Mean Square (RMS) value of a signal. RMS is a simple measurement of the fluctuating effect of the signal. RMS is defined to be the square root of the average of the sum of squares (Eq. (1)).

$$RMS = \sqrt{\frac{1}{N}\left[\sum_{i=1}^{N}(s_i)^2\right]} \qquad (1)$$

CF is calculated by dividing the peak value of a signal with the RMS of the signal (Eq. (2)). CF is based on the simple assumption that a signal with a few high amplitude peaks would produce a greater CF than a smooth signal. CF is a normalized parameter suitable for comparison between different measurements results.

$$CF = \frac{S_{\max}}{RMS} \qquad (2)$$

The results of the calculations of CF for the filtered recording of the gear notch fault and the gear play fault is shown in Figure 8 and in Figure 9 respectively.

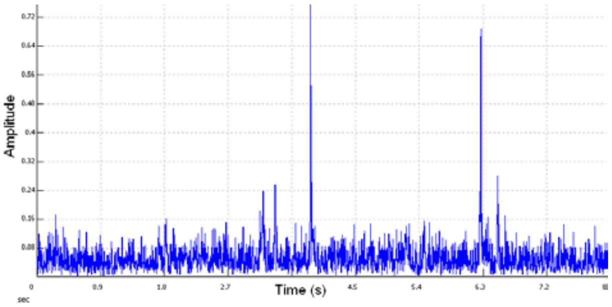

**Figure 8 CF on notch fault.**

The CF produces prominent peaks at each notch. The energy of the peaks is about seven times the average value of the CF.

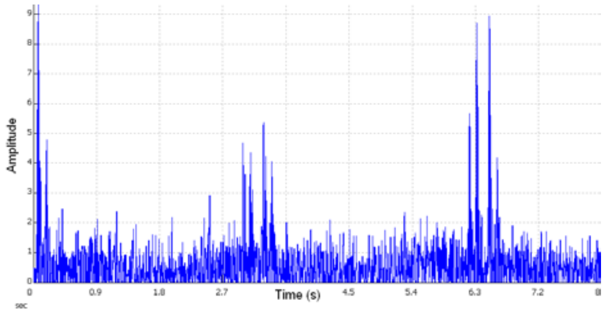

**Figure 9 CF on play fault.**

The CF produces prominent peaks at each change of rotation of the axis. The energy of the most prominent peaks is more than four times the average value of the CF. Results from calculations of the CF parameter can be seen in table 1.

**Table 1 CF parameter value from simulation and noise recordings.**

| **Test type** | **Variable parameters** | **Mean CF** |
|---|---|---|
| Torque | | |
| Simulation | Applied payload 10kg | 1.18-1.15 |
| Simulation | Applied payload 125kg | 1.15-1.13 |
| Simulation | Applied payload 200kg | 1.17-1.13 |
| | Faults type | |
| Filtered Noise spectrum | Gearbox in normal condition | 3.43 |
| Filtered Noise spectrum | Gearbox with play fault | 9.35 |
| Filtered Noise spectrum | Gearbox with notch fault | 14.6 |

The CF was calculated on two types of data:

1. On low pass filtered noise signals. Recorded from the gearbox of an industrial robot.
2. On the simulated torque from the input and output shaft of a dynamical model of the gearbox.

## Conclusions

CF is able to make a normalized parameter from a low pass filtered noise spectrum that can be useful for fault monitoring of the gearbox. The CF increased with more than 200 % on noise recordings in faulty case gearboxes in compare to recordings of normal gearboxes though. The simulation results are available for engineering design that can predict the tendency of faults development during the operating period subjected varying parameters such as inertia and external torque frequency/speed. Normal gearboxes with different payload setups were simulated in the component model and resulting in a low and stable CF. Those results are closer to the calculations of CF from the recording of the normal gearbox than to the CF of the noise recordings of the faulty gearboxes. The CF obtained from simulation and the experimental noise spectrum from the normal case gearbox is correlated.

Other useful results from this work consist in following: for comparative study of dynamical behavior and vibrations effects in gearboxes the statistical methods and factors are reasonable for faults detection.

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