inter.noise 2000
The 29th International Congress and Exhibition on Noise Control Engineering
27-30 August 2000, Nice, FRANCE

I-INCE Classification: 7.4

DETECTION OF IMPACT SOURCES USING AN IMPULSE RESPONSE RECOGNITION TECHNIQUE. APPLICATIONS ON RATTLE SOURCES IN GEARBOXES

J. Blomqvist

Dept. of Applied Acoustics, Svenhultinsgatan 8, SE-41296, Gothenburg, Sweden

Tel.: +4631 7722213 / Fax: +4631 7722212 / Email: jens@ta.chalmers.se

Keywords:
SOURCE, DETECTION, RATTLE, IDENTIFICATION

ABSTRACT

In this work a new method of localising sources is presented. This technique compares the structural response at a defined location with pre-measure characteristic responses. The characteristic responses are constructed from the structural response of the system together with a source model. The source identification is done by determining the correlation coefficient between the characteristic signals (representing the possible sources) and the analysed signal. Here the basic ideas and theory behind the technique are presented together with analysis results from case studies of rattling gearwheels in a gearbox of a truck.

1 - INTRODUCTION

This work deals with detecting gear rattle from trucks, which under certain engine speeds and loading conditions can dominate the total noise emitted from heavy vehicles, [1]. Additionally, truck manufacturers face demands of increasing power and lower engine speeds. As a consequence, noise due to gear rattle are expected to increase and so are also the demands on tools to analyse the noise. Furthermore, methods to reduce gear rattle are of growing importance due to overall vehicle refinement. Gear rattle can occur in gearboxes and results from gearwheels moving relative each other within the inevitable play between them. The relative motion generates rattle when mechanical contact is again obtained between the gearwheels. The perceived noise is a sharp impact sound. The method to detect gear rattle can be described as a pattern recognition technique. If a gearwheel is excited it will create a dynamic response on e.g. the gearbox casing. By measuring the dynamic response together with a model of force excitation of a rattle impact, it is possible to construct a characteristic response (CR). This CR will differ for all possible rattle sources (i.e. gearwheels) and should be possible to us as identifiers to recognise what is causing the noise when the gearbox is driven. In the following sections some background theory is presented together with analysis results from driven gearboxes.

2 - THEORY

The regarded situation is when an observed signal or response $r(k)$ due to an impact between two gearwheels is measured somewhere on e.g. the exterior of the gearbox.

If the acting force at the gearwheels are known and the system is linear and stationary, an impact between a particular set of gearwheels n will cause a CR $s_n(k)$ which should be possible to identify. In practise there will be noise in the analysis, which causes the observed signal will differ from CR. Now the problem of detecting rattling gearwheels can be divided into two sub-tasks, to decide which gear wheel is rattling and to determine the existence of gear rattle.

First the situation with an observed signal $r(k)$ corresponding to one of several original signals $s_n(k)$, which has been contaminated with noise, will be considered. The observed signal has a defined probability of being caused by the different possible original signals. This probability distribution is called the Likelihood Function (LF) of $r(k)$. The question is, what the origin was before it got polluted by noise, i.e. 'what was $s_n(k)$? Formally the task of choosing, which signal has been sent is referred to as a problem of Statistical Hypothesis Testing. If there is a "choice" of many possible sources, the choice should be made in a good way. Therefore a criterion which describes this "goodness" is needed. In

this work the criterion, used for choosing between signals is refereed to as the Maximum A Posterior probability (MAP) criterion [2]. This states that one should choose in favour of that signal s which has the highest probability of have been in the analysed signal or i.e. the $s_n(k)$, which is the most likely one according to the likelihood function. Considering rattle sources it is reasonable to assume that all sources are equally likely to rattle.
The test of the origin of which $r(k)$ can performed by evaluating the Correlation Coefficient (CC) (normalised correlation) between the observed signal and the possible signal as shown by [3]. A sample value of the CC with zero delay between the two signals can in discrete formulation be written according to

$$\rho_{s_n r}(0) = \frac{\sum_{k=1}^{N} s_n(k)\, r(k)}{\sqrt{\sum_{k=1}^{N} s_n^2(k) \sum_{k=1}^{N} r^2(k)}}$$

Which signal was sent can now be determined by simply determine which CR gives the largest CC. From equation 1 it can be seen that the maximum CC of unity is obtained when the observed signal and the CR used in the test are identical and there is no noise in the observed signal. Increasing the noise level will reduce the expectation of the CC. If the observed signal is tested with any other than the CRs the expectation becomes less than unity. The expectation of the CC becomes zero when either the signal to noise ratio of the analysed signal becomes zero, i.e. consists solidly of noise or when the observed signal and the CR are orthogonal. If the correlation above is carried out continuously it creates a function (CC) which is time depending. At each time instance the CC can be seen to give a value of how similar the two compared signals are.
If the noise can be regarded as white, the CC can be shown to be approximately Normal distributed [3] and hence if the variance of the noise is known, the probability of exceeding a certain CC can be determined. As a result this gives that if a threshold regarding the magnitude of the CC is set, the probability of falsely detecting a rattle response when there really was only noise can be calculated.
In practice Gear rattle can be of both periodic and non-periodic character and the time of occurrence is unknown. This feature has to be encountered for when performing the analysis. This is done by dividing the analysed signal into time segments and by detecting a maximum of one rattle event in each time segment. The analysis procedure can then be summarised in the following five steps:

- Define a CC threshold at the acceptable rate of false detection due to noise.
- Divide the signal into several time windows.
- Detect a message in a time window as soon as the CC due to any characteristic response, exceed the threshold.
- Choose that source location, i.e. gearwheel (represented by a characteristic response) with the highest probability of being the source.
- If needed, determine the probability of detection the correct source.

Dividing the analysed signal will causes additional errors e.g. when several rattle events occurs within the same segment. However if several time segments are used in the analysis and the task is to determine the main rattle contributor, this should not be of great importance. In "average" the correct source will be detected. In [3] it has been shown that the threshold for false detection due to noise can be estimated analytically while the rate of detecting a false source must be numerically determined. This last step is not necessary to do since the detector detects the source with the highest probability of being the correct source but it can be of interest when interpreting the results.

3 - ANALYSIS OF A GEARBOX WITH ONE RATTLE SOURCE

Experiments were carried out in a test rig, where the driving unit could induce angular variations on the input shaft as means to simulate engine firing. In order to control the experiment it was important that all sources of rattle were known. Therefore all rattle sources were removed except one acting pair of gearwheels. Although only one gearwheel could cause rattle, the analysis included altogether six rattle sources represented by their CR. An illustration of the gearbox and the possible source of gear rattle is demonstrated in figure 1. In order to validate the analysis results the rotational velocities of the two gearwheels in contact were measured. This supplied an answer to the question if the gearwheels were in continuous contact or if they were rattling.

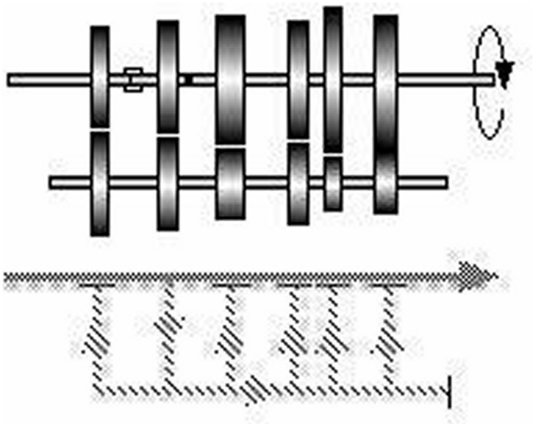

Figure 1: Reduced gearbox with one acting gearwheel pair, gearwheel 1 (gw1) and six possible sources of gear rattle (gw1-gw6); the gearwheels included in the test are shown as solid objects while the removed gearwheels are indicated by dotted lines.

The rattle analysis is done by first determining the Frequency Response Functions (FRFs) between the possible source of rattle and measurement positions on the gearbox casing. These FRFs are used to determine the CRs caused by an impact, which are compared with the gearbox casing vibrations at different driving conditions.
The dynamic system is described by measured FRFs between source locations and the chosen positions on the gearbox casing. Hence in order to obtain the CRs, a model of the source excitation is needed. The sources to be detected have the character of an impulse. A perfect impulse (a delta function) has a flat (frequency independent) frequency response function. Here the duration was assumed short enough to regard the response approximately flat to an upper frequency limit. This limit depends on the duration, and the shape of the true excitation together with the errors one is willing to accept. The true excitation is unknown and the frequency response of the excitation is assumed flat until 8 kHz. An example of the CRs is shown in figure 2.

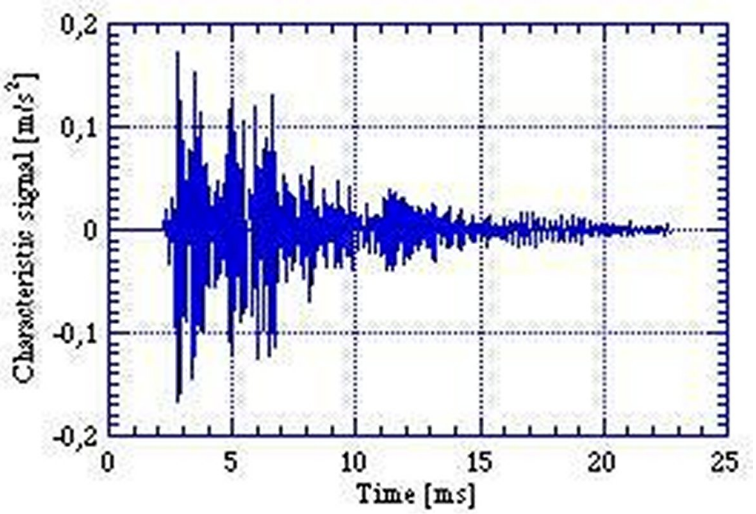

Figure 2: Example of a characteristic response on the gearbox casing due to an impact at a gearwheel. The signal is filtered with a 0,1-8,0 kHz band pass filter.

The acceleration on the gearbox casing was measured under different driving conditions with the focus on identifying situations with and without rattle. Here results at an engine speed of 1200 rpm, where a clear slightly irregular rattle noise was heard, is demonstrated. The velocity difference between the two driven gearwheels at 1200 rpm are shown in figure 3.

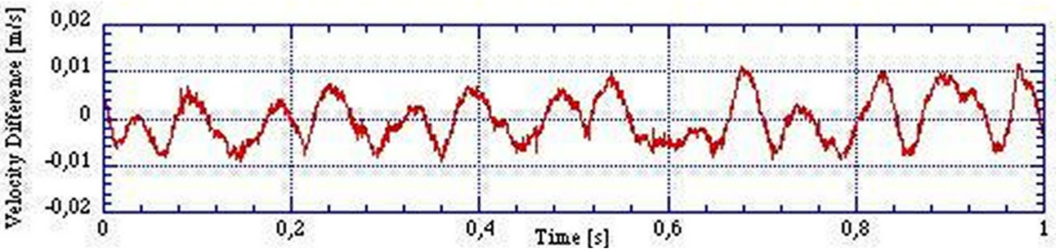

Figure 3: Velocity difference at engine speed 1200 rpm.

Figure 3 shows that under these driving conditions there is a relative velocity difference between the acting gearwheels, Furthermore. there seems to be events where a sudden change in velocity difference occurs. This behaviour would be expected in the case of e.g. gear rattle. The casing acceleration was analysed in five positions distributed on the gearbox casing. The analysis results depend on several parameters like e.g. filtering and the length of the characteristic signal. In the presented results a band pass filter of 0.1-8.0 kHz was applied on all signals and the length of the characteristic signals were 1600 samples where the sampling frequency was 44.1 kHz. The length of the CR effects the probability of detecting noise as a rattle event. The threshold was here set to 0.2 which corresponds to an error rate of 6·10-12 assuming that the noise can be regarded as approximately white.
The analysis results are presented for the five analysis positions as number of detected rattle events due to the six possible rattle sources (figure 4).

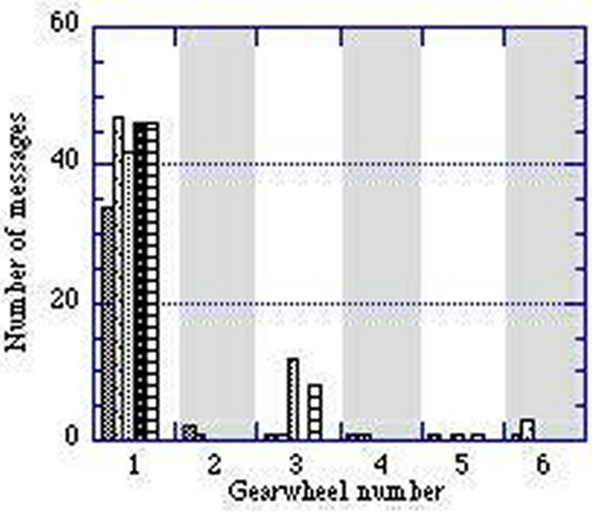

Figure 4: Number of detected rattle events (message) from gearwheels 1-6 at 1200 for five measurement positions; the threshold is set to 0.2, window length is 1600 samples, length of characteristic signals is 1600 samples and 2 seconds of data is analysed.

The results show that all measurement positions detect the right gearwheel pair as the main rattle contributor. Approximately 40 rattle events are detected. A few rattle events are dedicated from untrue rattle sources, i.e. the gearwheels that were excluded from the gearbox. The largest numbers of errors occurs in measurement position 3 and 5 due to the third pair of gearwheels. This correlated well with how similar in shape the different CRs are, i.e. of two sources has very similar characteristic functions it is difficult to distinguish between them. Other sources of errors are e.g. the presence of other disturbing sources and errors in the analysis model.

4 - ANALYSIS OF A GEARBOX IN AN ACCELERATING TRUCK

The analysis was carried out on a complete gearbox mounted in an accelerating truck where the gearbox was fixed in gear 6-high. This corresponds to that the power goes straight through the gearbox without changing revolution speed, i.e. the input shaft is locked on the output shaft. The counter shaft in the gearbox is now driven with the purpose of supporting a lubrication pump. The engine speed was varied between 12-29 rps (revolutions per second) and the analysis was carried out in four measurements positions on the gearbox casing. A schematic illustration of the power transmission trough the gearbox is shown in figure 5.

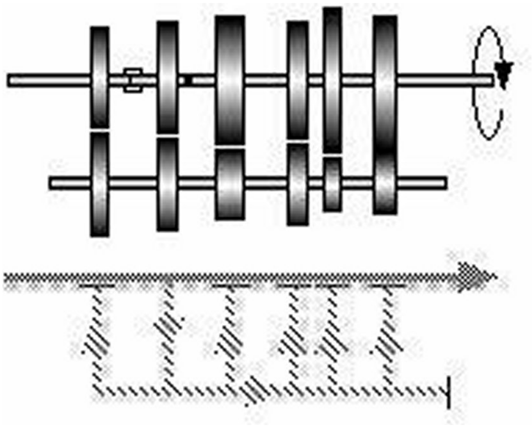

Figure 5: Power transmission trough the gearbox in gear 6-high.

The rattle model was the same as in the previous chapter although now the true sources of rattle were unknown and the length of the characteristic signals were 800 samples. Together with the noise threshold of 0.3, this gives a rate of errors due to mistaking noise as rattle events corresponding to 10-12. A sample of the results, obtained from analysing 2 seconds of data, is shown in figure 6. In order to detect a significant number of rattle events, it was necessary to filter the signals with a 4 kHz high pass filter. The reason for this was that at low frequencies other sources are dominating the vibrations. The results show that with an engine speed of 12 rps and with this choice of gears, the first pair of gearwheels in dominating the rattle. This showed to be independent with engine speed and corresponds well to what has been reported by e.g. [1]. The analysis results also point out other gearwheels as secondary sources.

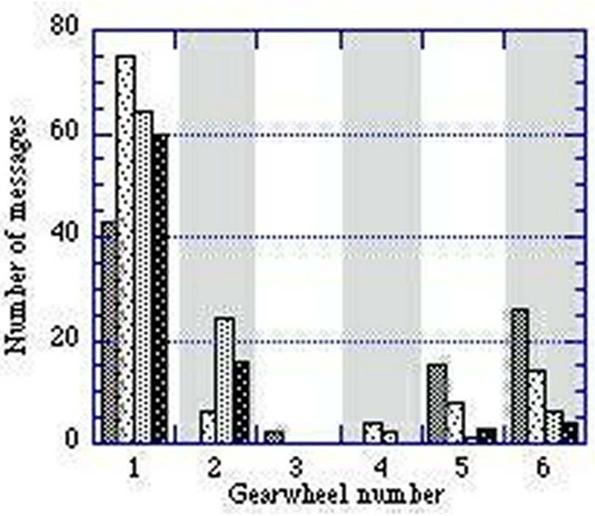

Figure 6: Number of detected rattle events (messages) from gearwheel 1-6 in the four measurement positions on the gearbox casing; the signals are filtered with a 4,0-8,0 kHz band pass filter and the analysed signal length is 2 seconds at the engine speed 12 rps.

5 - CONCLUSIONS

The basic principle of detecting sources using pre-measured characteristic responses (representing the possible sources) has been presented. The method has been illustrated and shown to work in the case of detecting rattle sources in gearboxes. The method can be described as a pattern recognition technique, where the distinction is made by the physical separation of sources. This permits source location/identification to be performed under conditions where other type of source monitoring is impossible.

A vital feature is that the quality of the analysis can be estimate regarded error types, which are well defined. These errors are the probability of detecting the wrong source and probability of mistaking noise as an acting source. The later has to be numerically calculated. However, if it is possible to rely on multiple rattle events, this is not necessary to determine, since the method in average detects the correct source.
Other types of errors in the analyses are related the model used for detection, e.g. regarding the noise assumptions, source excitation validity of characteristic signals and rattle sources.

REFERENCES

1. **F. Pfeiffer**, *Rattling in Gears - A Review*, VDI Berichte, 1996
2. **R. McDonough and al.**, *Detection of Signals in Noise*, Academic Press, San Diego., 1995
3. **Blomqvist**, *Detection of impact sources using an impulse response recognition technique. Application on rattle sources in gearboxes*, 1999