Identification of Noise Emission in a Gear Unit

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Today it is very important to ensure a stable production without unscheduled outages. To achieve this objective it is required to use advanced production technologies, to ensure adequate maintenance of mechanical systems and to monitor the condition of a device or machine. Reliable and accurate operation of machines and devices with as few outages as possible is desired. The significance of a life cycle design of machines and devices is growing. Possible damages in gear units can be defined by means of monitoring acoustic emission. A crack in the tooth root is usually indicated by significant changes in tooth stiffness. A difference in dynamic responses of an undamaged gear and of a damaged gear can be noted. The possibility of the use of an acoustic method in the field of condition diagnostics is dealt with. The noises produced by a gear unit have been analysed, the noise sources within a gear unit have been determined and the corresponding time-frequency analysis of these sources have been performed, using an acoustic camera.

1 Introduction

To maintain the characteristics of a technical system at the most favourable or still acceptable level is the primary goal of maintenance. In relation to this it is necessary to assess the condition of a technical system. For this purpose it is required to collect, analyse, compare and process data. On the basis of maintenance it is possible to reduce maintenance costs, and the frequency and complexity of damages, and to increase reliability of operation. Mechanical systems control can be effective only under the condition of precise data collection and proper data processing.

Gear units, which are most frequent machine parts or couplings, are of different types and sizes. A gear consists of a housing, toothed wheels, bearings and a lubricating system. The causes of durable damages in gear units are usually as follows: geometrical deviations or unbalanced component parts, material fatigue [2,8], resulting from the engagement of a gear pair, or damages of roller bearings.

When monitoring the condition of mechanical systems, it is often required to measure vibrations and noise; the methods used for this purpose are very suitable to obtain data on a gear unit. The data obtained in this way is then analysed. For this certain tools [7,9] are applied. In relation to this it is necessary to define the features indicating the presence of damages and faults.

2 Identifying noise source

Visualization of complex noise sources, using an acoustic camera, is presented. The basis for this is a new algorithm of digital signal processing; it enables visualization of all types of different complex noise sources from their far area. Monopole, dipole or quadropole noise sources, which occur simultaneously, can be observed. Besides, reflections from hard walls, refraction and scattering of sound waving can be detected.

If compared to the acoustic ray reconstruction method, the principle of acoustic camera operation differs from it to a great extent. Signals from all the microphones, which are located along the ring or the cross of the acoustic camera, are processed, in a rather complex way, by means of the acoustic camera algorithm. Corrections of individual signals are made, regarding their delay in relation to time, i.e. the length of the path made by sound waving from the elementary source to an individual microphone located in the camera. A delay is appropriately corrected in time domain, which differs from the sound ray reconstruction method [1, 2] in relation to which this is done by means of phases as in frequency domain.

Sound waving travels along paths r_i of various lengths from the elementary acoustic source $V(x_j)$ to an individual microphone on the ring of an acoustic camera (Fig. 1). The same sound waving, which is produced at the elementary sound source $V(x_j)$, causes different lengths of the path travelled by sound waving $|r_i|$, which leads to different signal delays Δ_i.

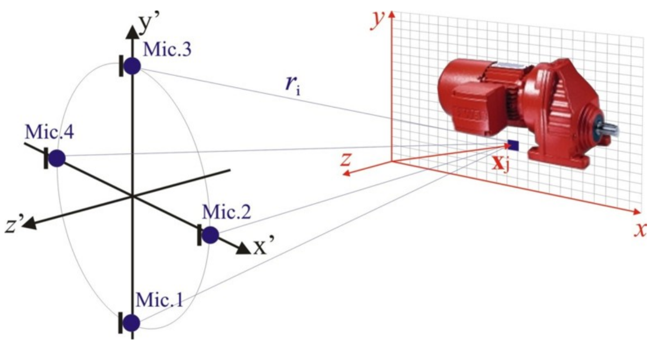

Fig. 1. Length of the path of an elementary source to individual microphones located on an acoustic camera

The basis of an acoustic camera presents the so called Heinz Interference Transformation algorithm. By approximating the original acoustic source in the best way possible (by moving forward and backward simultaneously), it creates a pseudo inverse acoustic field with interference integrals. The algorithm realises time-negative reconstruction in a time positive way [3]. The result is a surface of equivalent acoustic pressure at the point of greatest emission.

Under the assumption that sound waving from each elementary source comes to each microphone on the ring of the acoustic camera, it is possible to, in time, shift and integrate signals that come from different microphones as appropriate. A new signal $f(x_j,t)$ is acquired for each elementary source, using the following equation:

$$\hat{f}(\mathbf{x}_j,t) = \frac{1}{M}\sum_{i=1}^{M} w_i f_i(\mathbf{x}_j,(t-\Delta_i)) \qquad (1)$$

The effective value of the sound pressure $f_{eff}(x_j,t)$ is then calculated on the basis of this signal:

$$p_{eff}(\mathbf{x}_j) \approx p_{eff}(\mathbf{x}_j,n) = \sqrt{\frac{1}{n}\sum_{k=0}^{n-1}\hat{f}^2(\mathbf{x}_j,t_k)} \qquad (2)$$

The effective sound pressure, which is caused by the elementary acoustic signal at the spot of emission, represents a mean square value of the acoustic pressure. The corresponding point in the acoustic image is to be coloured as required; this depends both, on the position of the elementary source and on the value of its effective acoustic pressure. High effective sound pressure areas are usually coloured in red, whereas areas with lower effective sound pressure are blue, which gradually fades until, finally, these areas become white. In order to obtain the entire acoustic image of the acoustic source, it is required to repeat the procedure for each elementary source. If several individual acoustic sources form an acoustic source, it can be determined, on the basis of the acoustic image, which acoustic source at the measurement spot contributes mostly to effective acoustic pressure.

The form of sound signals has an important impact upon the resolution of place and time of acoustic image, produced with an acoustic camera. In regard to the algorithm of the acoustic camera, the form of an impulse of sound pressure is ideal, whereas pure sine-shaped form of acoustic waving is the least favourable sound pressure phenomenon. All real sound pressure phenomena are actually between these two forms. Almost the entire acoustic theory, including the theory of acoustic ray reconstruction method and the theory of image method in a nearby field, is based on the sinus function, i.e. on the Fourier area. Pure sine-shaped form is very rare when speaking of real sound/noise signals. This means that the acoustic camera algorithm has a much greater practical value than other algorithms that have been developed so far.

The only method of visualization of acoustic sources that function exclusively in time domain is acoustic camera; it is not required to use the Fourier transform to calculate the acoustic image. This means that the acoustic camera has no limitations that are usually associated with the use of the Fourier transform. As a matter of fact, frequency analysis is integrated in the user system, but the algorithm calculates the acoustic image first and only after that also the Fourier transform.

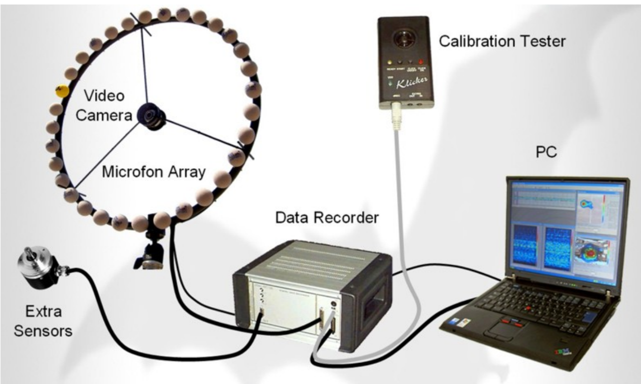

Fig. 2. An acoustic camera system GFaI for visualisation of acoustic sources

Fig. 2 presents the measurement system in relation to the acoustic camera of the GFaI with dRec48C192; there are 32 phase coordinated microphones, which are located on a ring in relation to the work in a free acoustic field. For an acoustic camera, prepolarised condensation microphones with linear frequency of 23 kHz (–3 dB) are applied. Their response is gradually reduced from 6 dB per decade to 40 kHz. As a result of the requests regarding the resolution of the acoustic image, it is necessary to use microphones with such a high frequency area. It is possible to achieve higher resolution in relation to higher sampling frequencies or by means of better phase coordination of microphones.

An analogue-digital converter functions with a 21 bit resolution, whereby the highest sampling frequency is 196 kHz per channel. During measurement, digitalised signals are temporarily stored in this converter. After that the data is transferred to a personal computer. This takes a few seconds. Afterward it is possible to calculate the sound source acoustic image.

3 Analysis of acoustics emission

A gear unit makes the transmission of rotating movement possible. In spite of the fact that a gear unit is a very complex dynamic model, the rotating movement is usually periodical. Faults and damages, which represent a disturbing quantity or impulse, are indicated by local and time changes in vibration signals; this means that time-frequency changes can be expected [5].

The following factors have the most negative impact on the reliability of operation and adequate quality of operation of gear units (they are listed from the largest to the least important factor): the presence of cracks (notches) in gear units, wear and tear of teeth flanks and eccentricity caused by backlash in bearings, errors when assembling and manufacturing gear units. Usually, a frequency spectrum is applied in order to define deviations from reference values. Here it must be emphasised that a gear unit is a complex mechanical system with changeable dynamic reactions; as a result it is impossible to define modifications of a frequency component in time. Instead, it is required to apply the approach based on time-frequency methods.

When speaking of technical diagnostics it has to be mentioned that there are some frequency components in signals that often appear only occasionally. In order to establish when certain frequencies appear in a spectrum, it is not adequate to carry out classical frequency analysis. Time-frequency analysis makes it possible to describe in what way frequency components of non-stationary signals change with time; in addition to that it also makes it possible to define their intensity levels.

4 Practical example

The test plant of the Acoustics Laboratory of the Faculty of Mechanical Engineering, University of Ljubljana, has been used to carry out the measurements.

A single stage gear unit RX57 DR63S4 produced by SEW-EURODRIVE with a helical gear unit with straight teeth integrated into it was used.

The excitation of a gear directly in the meshing area was caused by the following internal sources: the impact at the beginning of meshing, tooth stiffness producing parametrical excitation, geometrical deviations of teeth and deformation of bearings and shafts. A crack (notch) in the tooth root produces significant changes in tooth stiffness.

The dynamic response in relation to a damaged tooth differs from the one in relation to an undamaged tooth. In relation to the practical example, a notch was produced first. This was done in order to simulate the conditions close to the ones relating to a fatigue crack in a tooth root. There are, however, certain differences between a crack and a notch, the most significant ones being: a notch is thicker than a crack; a notch is flat whereas a crack propagates in the direction of the gradient of maximum stresses; the boundary of a notch is flat, which is usually not the case with cracks (Fig. 3).

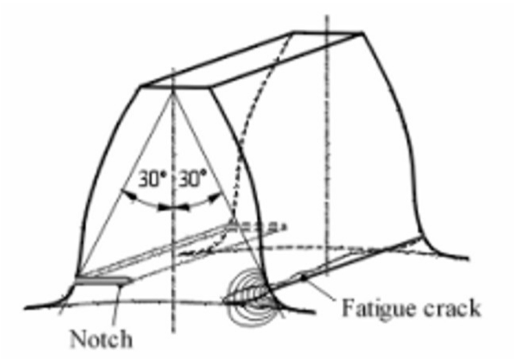

Fig. 3. Differences between a notch and a fatigue crack in a tooth root

Noise produced by two pairs of spur gear-units, integrated in a single stage gear-unit, was measured. One of the pairs had a notch, whereas the other one was without it. Tests under different loads were performed. Since a sensor has to be placed directly on a gear-unit or even fixed on it, it is simpler to measure noise than vibrations. This is one of the reasons why a signal that was to be analysed had been acquired by measuring noise (using microphones) and not vibrations (using accelerators) although the signal of vibrations is closer to the actual responses of gear-units.

Slight modifications were made to the gear unit so as to artificially produce faults and damages in a gear pair and to adapt some design-related features in relation to the test plant. In addition to that, measurements were performed in order to identify the presence of individual changes in a gear unit. The basis of the method used to determine the condition of a gear unit represents the comparison between the measured signal produced by a faultless gear unit and the signal of a faulty gear unit. Thus, faultless and faulty gear units were used to perform tests.

Thus, measurements of a gear unit with a notch in the tooth root of a pinion were performed; the operating conditions were such as are usually associated with this type of a gear unit. A standard gear pair, with the teeth quality 6A, was used as a ground gear pair with a notch; the notch was located in the tooth root of a pinion. It is shown in Fig. 4.

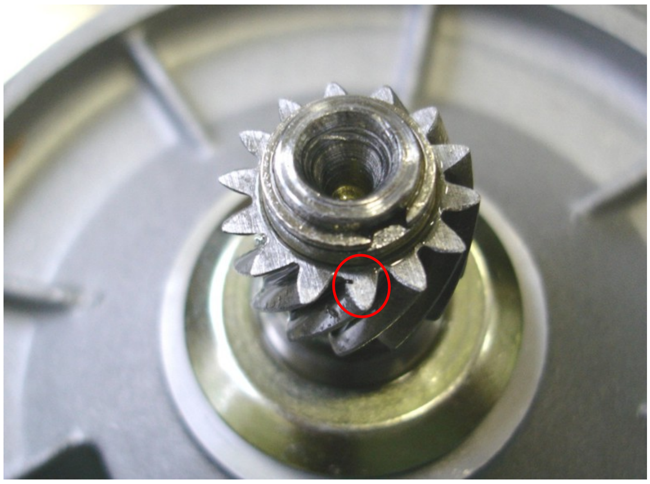

Fig. 4. Pinion with a notch in the tooth root

The length of the notch in one of the teeth was 1 mm. Both, the measurement and the preparations for analysis are presented in detail in [5].

In order to determine the presence of a notch in the tooth root, Short time frequency transform was used.

The length of the measured values of the signal was 2 s; the signal was composed of, on an average, 192000 measuring points. At the time of measurement, the rotational frequency was 35 Hz. The number of teeth of the pinion was 14, and of the gear unit 77.

The acoustic image and the spectrogram are shown in Fig. 5; no rhythmic pulsation of harmonics can be observed, with the exception of typical frequencies, determined on the basis typical frequencies components. Some pulsation sources are indicated. They are, however, not very expressed. Monitoring the increase or decrease (complete disappearance) in appropriate frequency components with pulsating frequency is particularly interesting. This is typical of meshing frequency (500 Hz) and high harmonic. Only in relation to the presence of a notch, pulsating is expressed. This phenomenon is presented in Fig. 6 and 7. Pulsation is expressed, which reflects a single engagement of a gear pair that has a notch. Similarly (Fig. 7), sources indicate pulsating portions of individual components between the 1st and the 2nd harmonics.

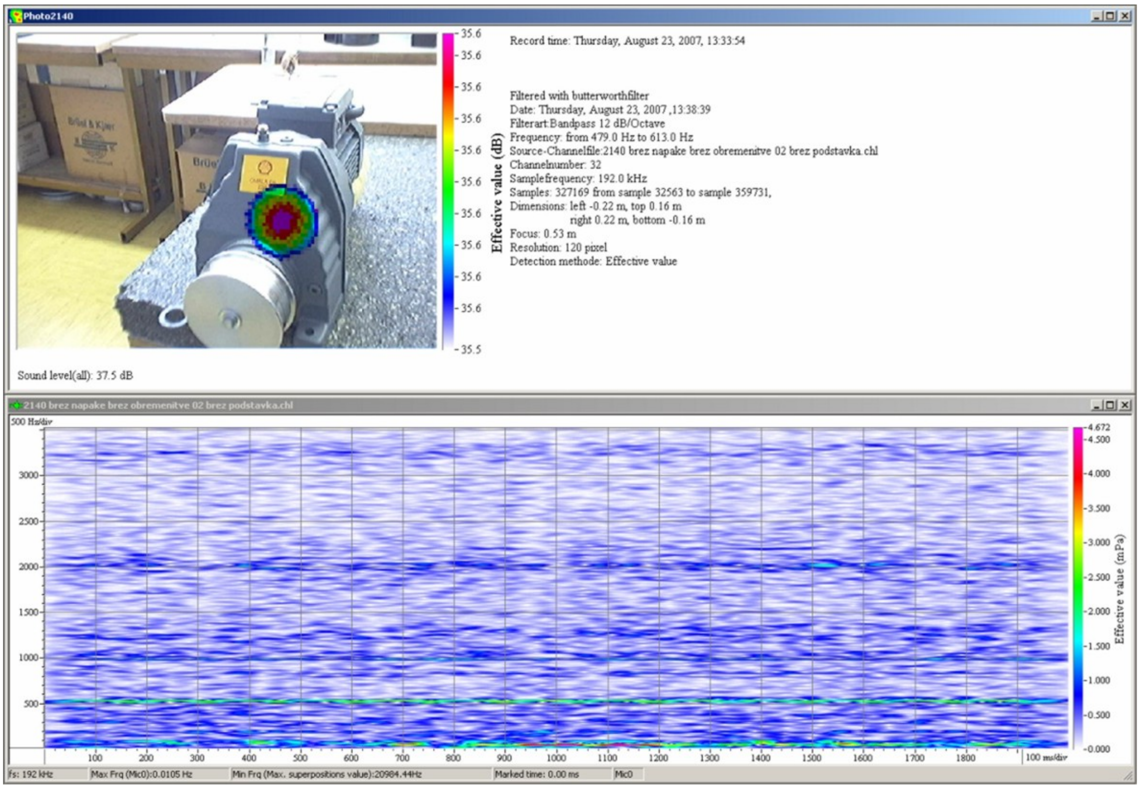

Fig. 5. Acoustic image with spectrogram of a faultless gear

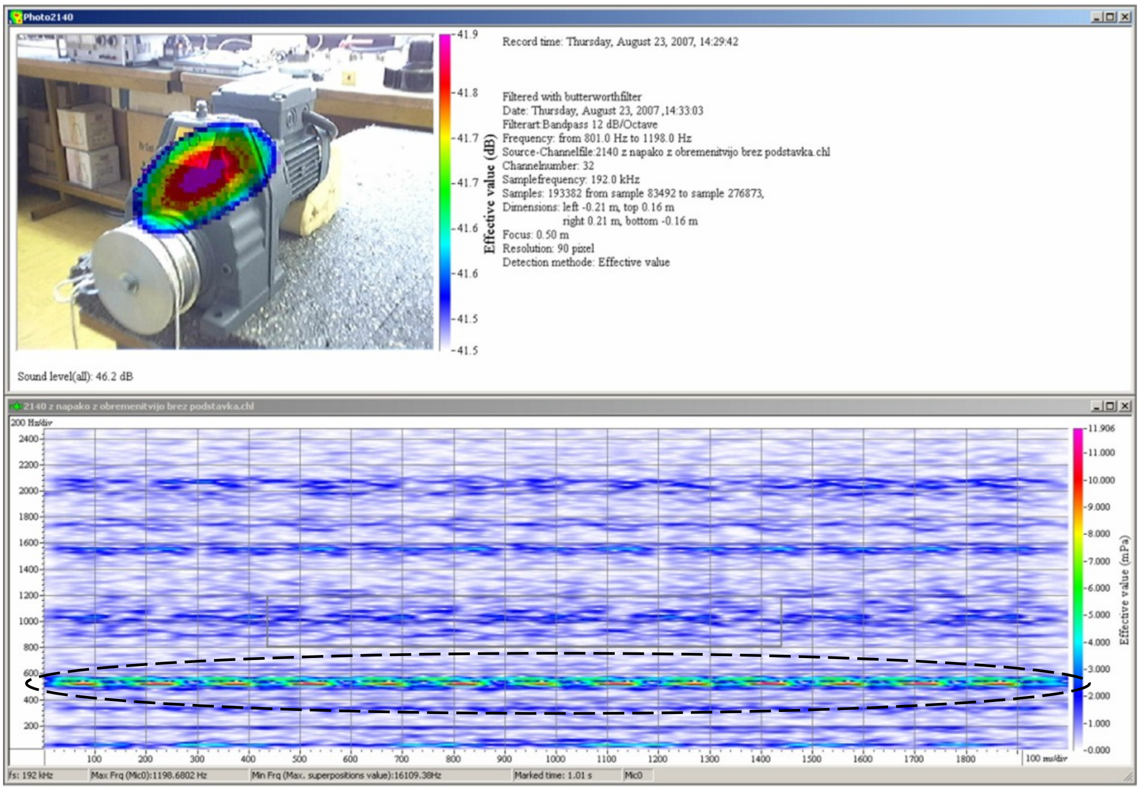

Fig. 6. Acoustic image with spectrogram of a gear unit with a notch in the tooth root

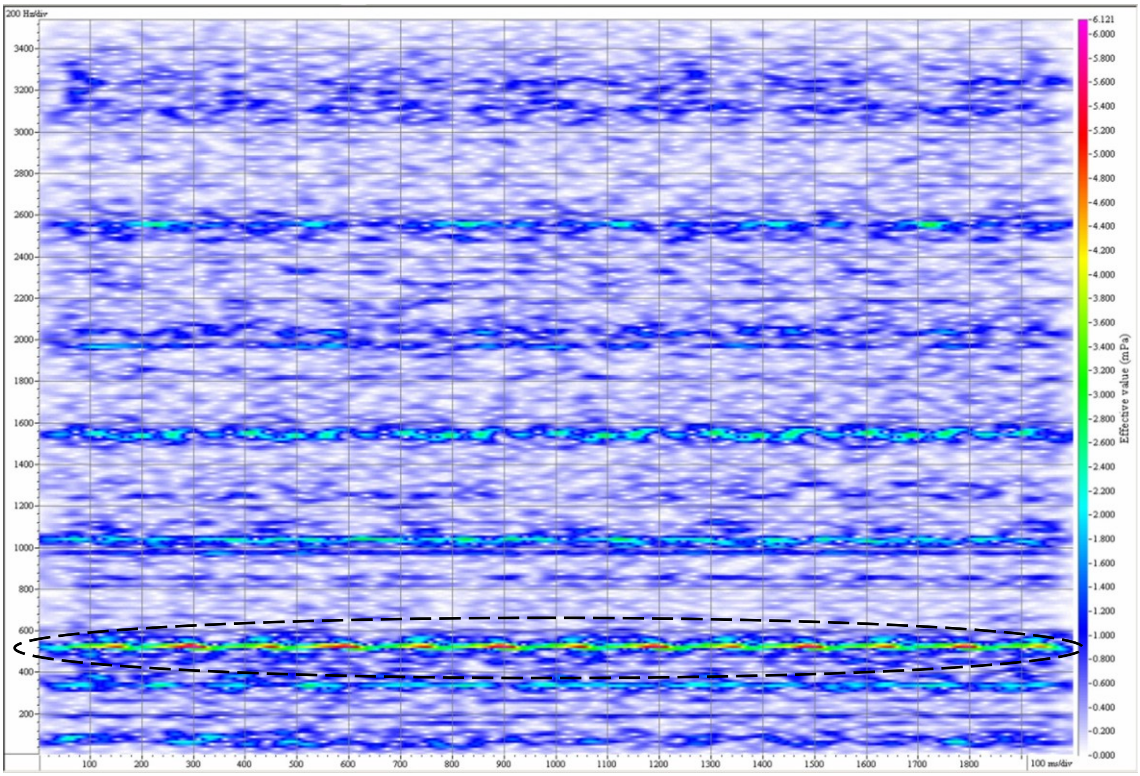

Fig. 7. Spectrogram of a gear unit with a notch in the tooth root, position 4

5 Conclusion

A better resolution in relation to time and place of visualisation of acoustic sources is possible on the basis of the use of an acoustic camera with its specific algorithm that functions in time domain and on the basis of specifically located microphones than on the basis of any other acoustic system.

For noise analysis, industrial gear units have been used; the purpose of the analysis was to detect faults. On the basis of the presented methods, the safety of operation can be increased, along with the reliability of monitoring operational capabilities.

It is more reliable to monitor the life cycle of a gear unit if appropriate spectrogram samples and a clear presentation of the pulsation of individual frequency components are applied, which, along with the average spectrum, represent a criterion for assessing the condition of a gear unit.

When speaking of life cycle design, an adequate method or criterion can be used to monitor the actual condition of a device and its vital component parts, which can influence the operational capability in a considerable way. Considerable control of the reliability of operation can be ensured if faults and damages are detected in time. The use of reliable methods for detecting faults improves the prediction of the remaining life cycle of a gear unit.

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