 SDHM, vol.3, no.4, pp.239-246, 2007

Analysis of Noise Sources Produced by Faulty Small Gear Units

Aleš Belšak[1] and Jurij Prezelj[2]

Abstract: Noise source vizualization represents an important tool in the field of technical acoustics. There are many different techniques of noise source visualization. Most of them, however, are intended for a specific noise source in a specific type of acoustic environment. Consequently, a certain visualization method can be used only for certain types of noise sources in a specific acoustic environment and in a restricted frequency area. This paper presents a new visualization method of complex noise sources on the basis of the use of an acoustic camera. A new algorithm has been used, which makes it possible to visualize all types of different complex noise sources. Monopole, dipole or quadropole noise sources can be observed simultaneously. It is possible to track a moving noise source by means of an acoustic camera. In addition to that it is possible to observe various transient acoustical phenomena. Through the use in diagnostics, it is possible to define, by means of noise, the condition of mechanical systems at an advance level.

Keyword: Gear, Failure, Sound, Acoustic Camera, Signal Analysis, Acoustic Image

1 Introduction

The main goal of maintenance is to maintain the characteristics of a technical system at the most favourable or still acceptable level. In order to assess the condition of a technical system it is necessary to collect, analyse, compare and process data. It is possible to reduce maintenance costs, increase the reliability of operation as well as decrease the frequency and complexity of damages. It is only possible to control mechanical systems effectively if precise data is collected and then properly processed.

Gear units are most frequently used machine parts or couplings; gear units consist of a housing, toothed wheels, bearings and a lubricating system and are of different types and sizes. The main causes of durable damages in gear units are usually geometrical deviations or unbalanced component parts, material fatigue [2,8], which results from the engagement of a gear pair, or damages of roller bearings.

In relation to monitoring the condition of mechanical systems, methods for measuring vibrations and noise are often used; they are suitable to acquire data on a gear unit. After that data analysis is carried out, for which certain tools [7,9] are used; the main purpose is to define the features indicating the presence of damages and faults.

2 Noise Suorce Indentification

A visualization method of complex noise sources by means of an acoustic camera, which is presented in this paper, is based upon a new algorithm of digital signal processing. It enables visualization of all types of different complex noise sources. Thus, observation of monopole, dipole or quadropole noise sources, which occur simultaneously, is possible. In addition to that, detection of reflections from hard walls, refraction and scattering of sound waving are possible.

Acoustic camera operation is, in principle, very different from the acoustic ray reconstruction method. Signals are obtained via microphones, placed on the ring or the cross of an acoustic camera; on the basis of the acoustic camera algorithm they are processed in a rather complex way. The algorithm corrects individual signals regard-

[1] University of Maribor, Faculty of Mechanical Engineering, Smetanova 17, Maribor, Slovenia. Email: ales.belsak@uni-mb.si

[2] University of Ljubljana, Faculty of Mechanical Engineering, Aškerčeva 4, Ljubljana, Slovenia. Email: jurij.prezelj@fs.uni-lj.si

ing their delay in relation to time, i.e. the length of the path of the sound waving from the elementary source to an individual microphone located on the camera. The delay is appropriately corrected in time domain and not by means of phases as in frequency domain, which happens in relation to the sound ray reconstruction method [1, 2].

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). As the path lengths travelled by sound waving $|ri|$ are different, signal delays Δ_i of the same sound waving, which is produced at the elementary sound source $V(x_j)$, are also different.

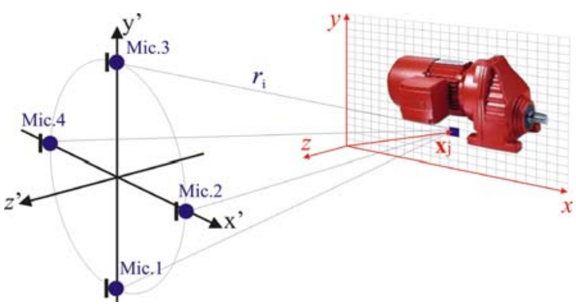

Figure 1: Path length of an elementary source to individual microphones located on an acoustic camera

An acoustic camera is based on the Heinz Interference Transformation algorithm; this algorithm produces a pseudo inverse acoustic field with interference integrals; this is done by approximation of the original acoustic source in the best way possible: by moving forward and backward simultaneously. Time-negative reconstruction is realized in time positive way [3]. This leads to a surface of equivalent acoustic pressure at the point of greatest emission.

Based on the assumption that each microphone on the ring of the acoustic camera is reached by sound waving from each elementary source, 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 obtained for each elementary source, using the following equation:

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

On the basis of this signal the effective value of the sound pressure $f_{eff}(x_j,t)$ can be calculated:

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

The effective sound pressure is a mean square value of the acoustic pressure; at the spot of emission, it is caused by the elementary acoustic signal. The corresponding point in the acoustic image is to be coloured as required – depending on the position of the elementary source and the value of its effective acoustic pressure. The colour of areas with high effective sound pressure is usually red, and areas with lower effective sound pressure are usually blue, which gradually fades until they become white. For each elementary source, the procedure has to be repeated so as to acquire the entire acoustic image of the acoustic source. If an acoustic source consists of several acoustic sources, it can be, on the basis of the acoustic image, discovered, which acoustic source at the measurement spot primarily contributes to effective acoustic pressure.

The form of sound signals influences the resolution of place and time of acoustic image, produced with an acoustic camera. If the algorithm of the acoustic camera is taken into consideration, an impulse of sound pressure has an ideal form; the pure sine-shaped form of acoustic waving, however, is the least favourable sound pressure phenomenon. All real sound pressure phenomena are between the two mentioned forms. The sinus function, i.e. the Fourier area, represents the basis for almost the entire acoustic theory; this includes the theory of acoustic ray reconstruction method and the theory of image method in a nearby field. As pure sine-shaped form is very rare when speaking of real sound/noise signals, the acoustic camera algorithm has a greater practical value than other algorithms developed so far.

Acoustic camera is the only method of visualization of acoustic sources that function exclusively in time domain; it is not necessary to use the Fourier transform to calculate the acoustic image. Acoustic camera, therefore, has no limitations that are usually associated to the use of Fourier transform. It is true that frequency analysis is integrated in the user system but the algorithm calculates the acoustic image first and the Fourier transform only after that.

Fig. 2 shows the measurement system based on the acoustic camera of the GFaI with dRec48C192 and 32 phase coordinated microphones, which are placed 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 used. Their response is gradually reduced from 6 dB per decade to 40 kHz. In view of the requests regarding the resolution of the acoustic image, microphones with high frequency area are necessary. In relation to higher sampling frequencies or better phase coordination of microphones it is possible to achieve higher resolution.

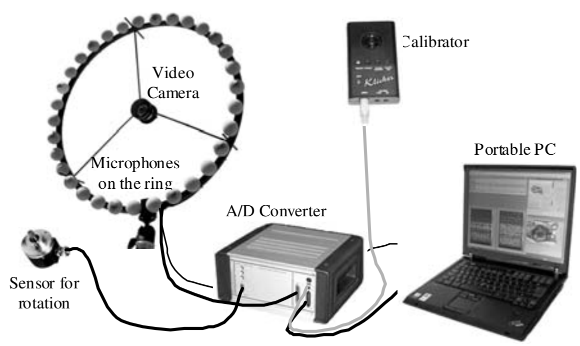

Figure 2: An acoustic camera system GFaI for visualisation of acoustic sources

An analogue-digital converter functions with a 21 bit resolution; the highest sampling frequency is 196 kHz per channel. In this converter, digitalised signals are temporarily stored during measurement. The data is then transferred to a personal computer; after that it is possible to calculate the sound source acoustic image.

3 Time-Frequency Analysis of Acoustic Emission

A gear unit makes the transmission of rotating movement possible. Although a gear unit represents a complex dynamic model, this movement is, in most cases, periodical. Thus, faults and damages represent a disturbing quantity or impulse, and are indicated by local and time changes in vibration signals; consequently, it is possible to expect time-frequency changes [5].

The reliability of operation and adequate quality of operation of gear units is influenced most negatively by the presence of cracks (notches) in gear units; this is followed by wear and tear of teeth flanks and eccentricity caused by backlash in bearings; errors when assembling and manufacturing gear units are the third most negative factor. Deviations from reference values are usually identified on the basis of a frequency spectrum. A gear unit is a complex mechanical system with changeable dynamic reactions; therefore, modifications of a frequency component cannot be defined in time, but it is required to use the approach based on time-frequency methods.

Some frequency components in signals often appear only occasionally. Classical frequency analysis of such signals is not sufficient in order to establish when certain frequencies appear in a spectrum. On the basis of time-frequency analysis it is possible to describe in what way frequency components of non-stationary signals change with time and, in addition to that, to define their intensity levels.

4 Practical Example

The test plant of the Laboratory for Technical Acoustics of the Faculty of Mechanical Engineering, University of Ljubljana has been used for the measurements. A single stage gear unit RX57 DR63S4 (electromotor with power 120W), which was produced by SEW-EURODRIVE and which had a helical gear unit with straight teeth integrated into it, was used. A, in relation to small gear, the distance between the teeth is very small, it is difficult to produce a fatigue crack in a tooth root with maschine for dynamic tests. Therefore a notch in the tooth root was produced by means of wire erosion.

Excitation of a gear was caused directly in the meshing area, using 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 caused important changes in tooth stiffness. The result in a dynamic response differed from the one in relation to an undamaged tooth. The purpose of the notch, which had been produced, was to simulate the conditions close to the ones in concern to a fatigue crack in a tooth root. It must be mentioned, however that it is possible to observe differences between a crack and a notch. The most important differences are as follows: 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).

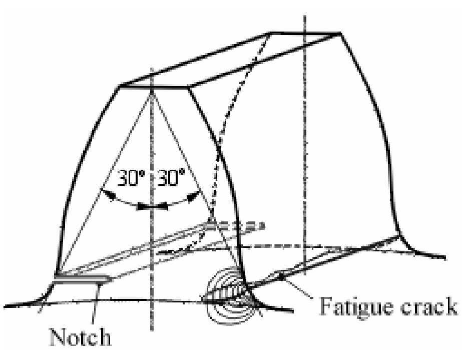

Figure 3: Differences between a notch and a fatigue crack in a tooth root

Using two pairs of spur gear-units, built in a single stage gear-unit, noise measurements were performed. One of the pairs had a notch and the other one was without it. Tests under different loads were performed. As a sensor has to be placed directly on a gear-unit or even fixed on it, it is simpler to carry out noise measurement than vibration measurement. This is one of the reasons why the acquisition of a signal that was to be analysed had been carried out by noise measurement (using microphones) although vibration measurement (by means of accelarators).

Slight changes of a gear unit were produced so as to artificially produce faults and damages in a gear pair and to adapt some design-related features in regard to the test plant. Besides, measurements were performed to identify the presence of individual changes in a gear unit. The method of establishing the condition of a gear unit was based on comparing the measured signal of a faultless gear unit with the signal of a faulty gear unit. Tests were carried out, using faultless and faulty gear units. Measurements of a gear unit with a notch in the tooth root of a pinion were performed; the operating conditions were such as they are usually associated with this type of a gear unit. A ground gear pair with a notch was a standard gear pair, with the teeth quality 6; the notch was located in the tooth root of a pinion. It is presented in Fig. 4. The length of a notch in one of the teeth is 0.8 mm.

Figure 4: Pinion with a notch in the tooth root

Short time frequency transform was used to establish the presence of a notch in the tooth root. The length of the signal of measured values was 2 s; on an average, the signal was composed of 192000 measuring points. At the time of measurement, the rotational frequency amounted to 35 Hz. The number of teeth of the pinion was 14, and of the gear unit 77.

Fig. 5 and 6 show the acoustic image and the spectrogram; it is not possible to observe any rhythmic pulsation of harmonics, with the exception of typical frequencies, established on the basis of typical frequencies components. Some pulsation sources can be noticed although they are not very expressed and are stohastic. Monitoring the increase or decrease (complete disappearance) in appropriate frequency components with pulsating frequency is very interesting. This is typi-

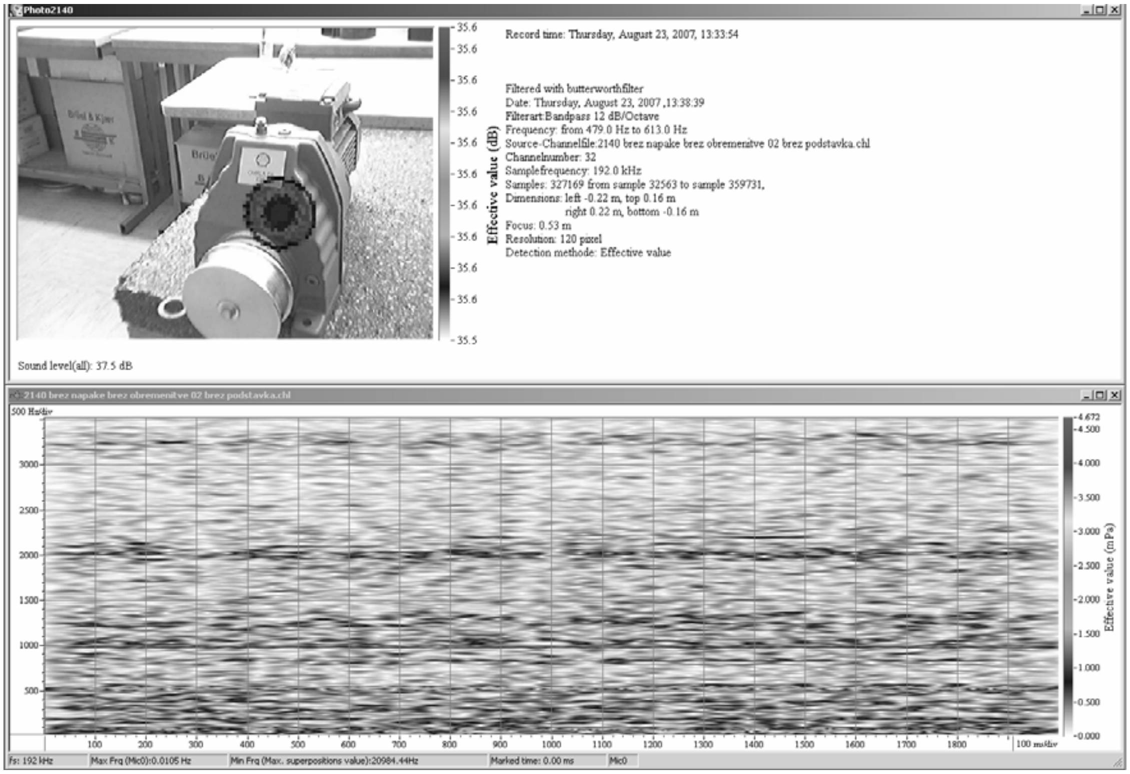

Figure 5: Acoustic image with spectrogram of a faultless gear, position 1

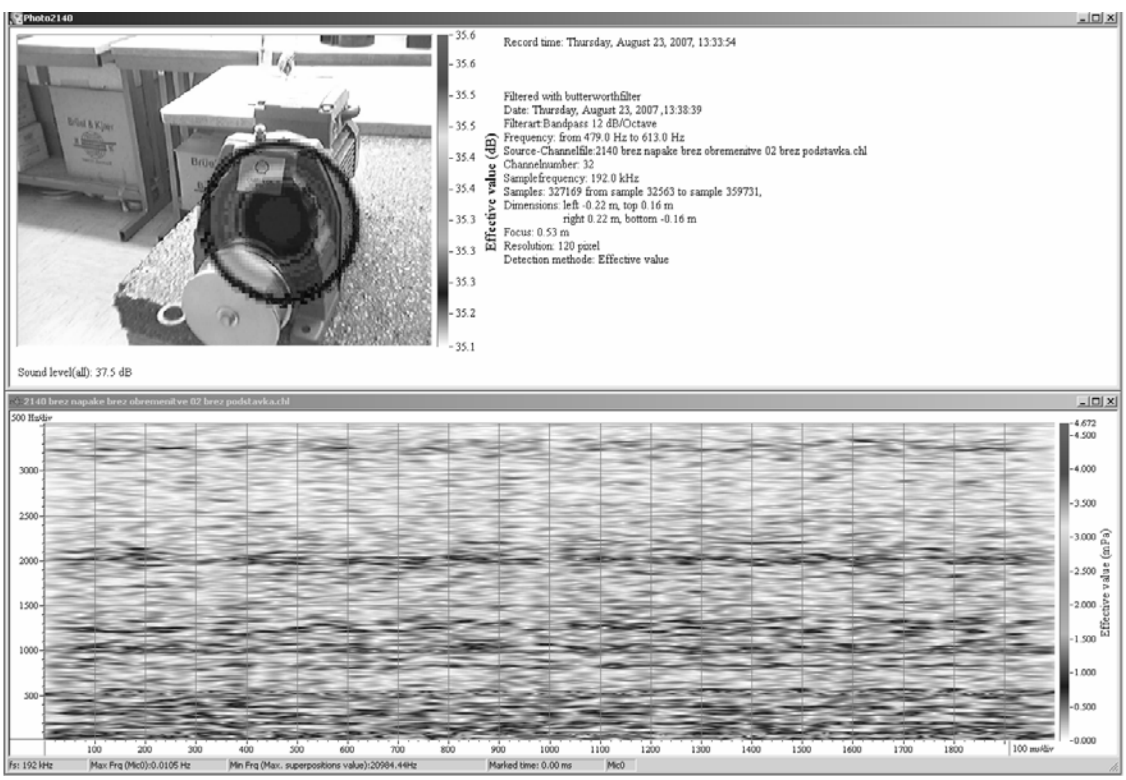

Figure 6: Acoustic image with spectrogram of a faultless gear, position 2

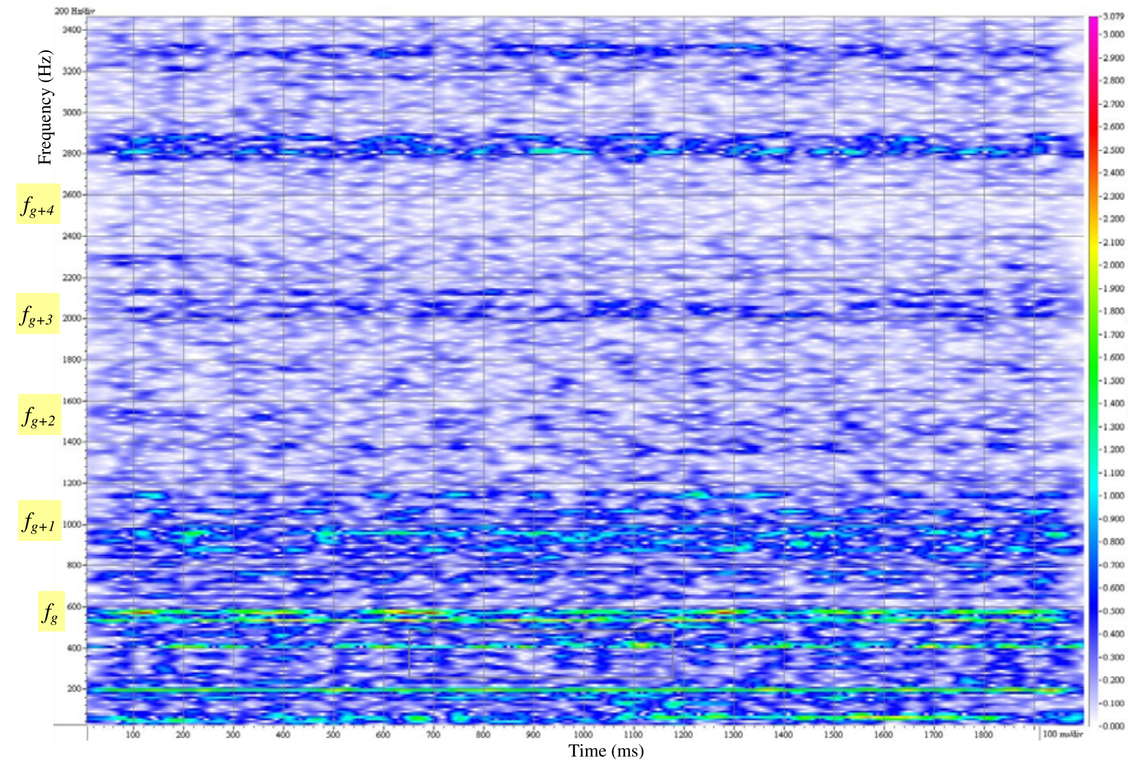

Figure 7: Spectrogram of a a faultless gear, position 2

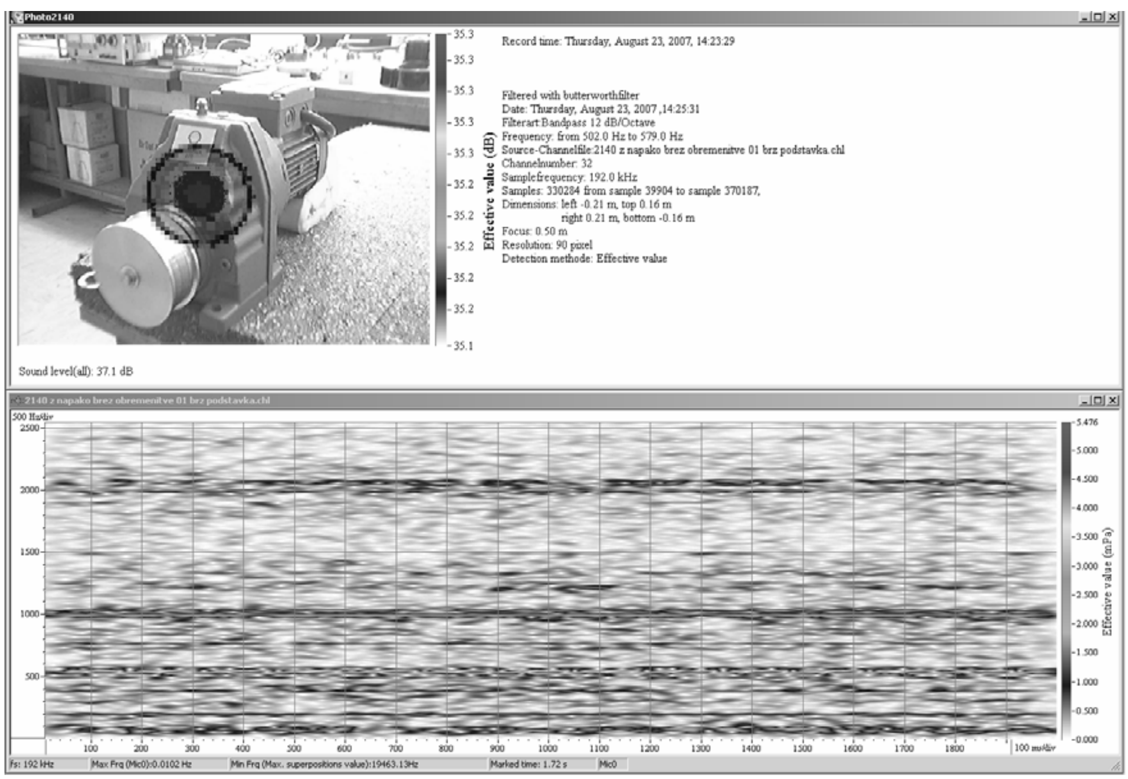

Figure 8: Acoustic image with spectrogram of a gear unit with a notch in the tooth root, position 3

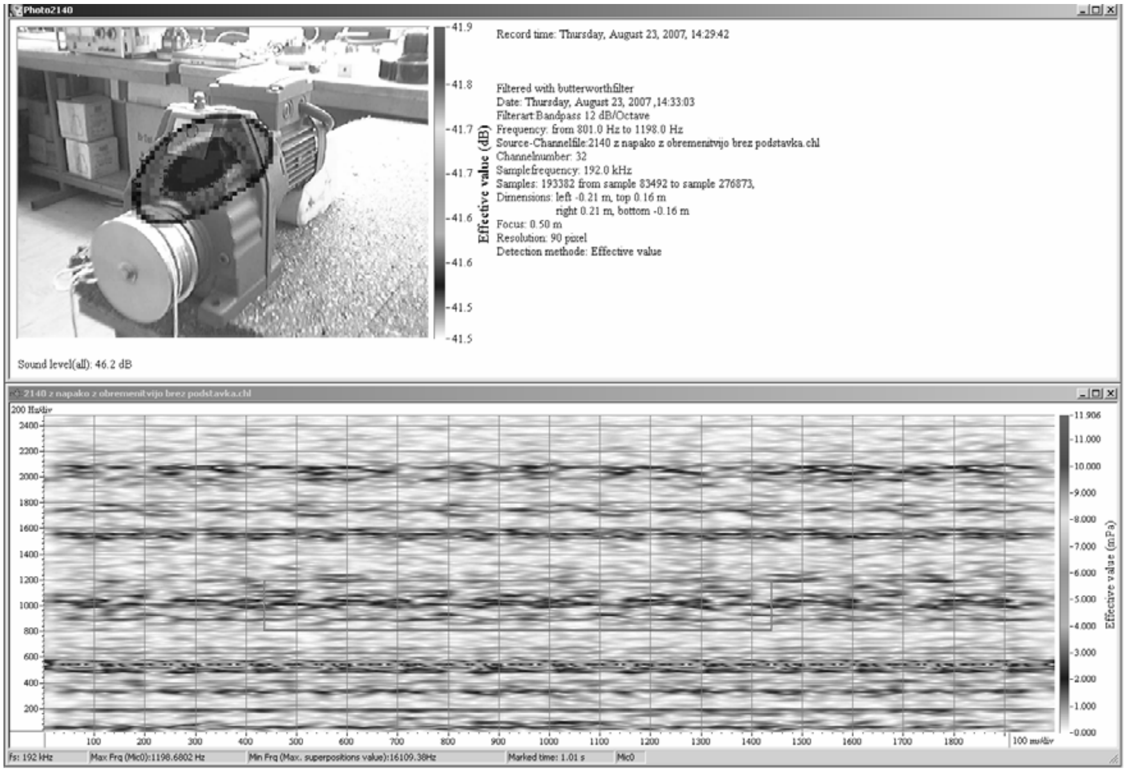

Figure 9: Acoustic image with spectrogram of a gear unit with a notch in the tooth root, position 4

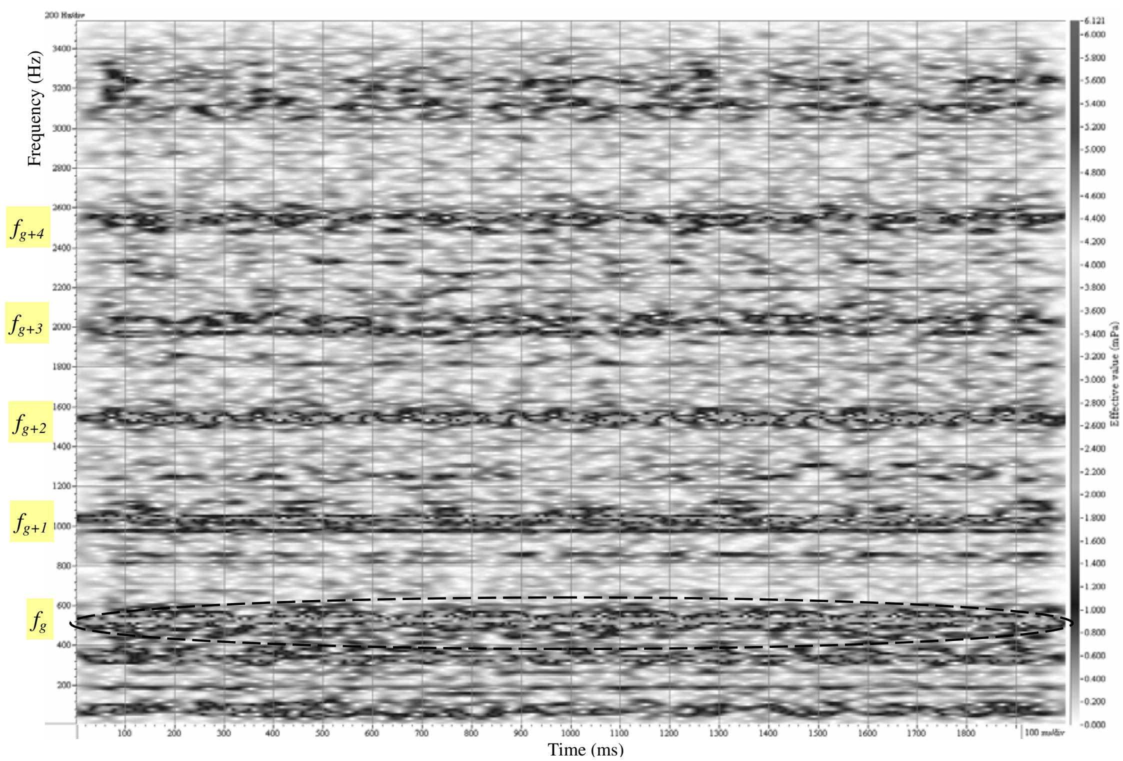

Figure 10: Spectrogram of a gear unit with a notch in the tooth root, position 4

cal for meshing frequency (500 Hz) and for high harmonic. Figures 5, 6 and 7 show only typical meshing frequency and high harmonics without periodical pulsation of individual frequency components.. Pulsation is expressed only in association to the presence of a notch. Fig. 8, 9 and 10 present this phenomenon. Expressed pulsation reflects a single engagement of a gear pair with a notch. Similarly (Fig. 10), sources between the 1st and the 2nd harmonics indicate pulsating portions of individual components.

5 Conclusion

With its specific algorithm functioning in time domain and on the basis of specifically located microphones, an acoustic camera enables the visualisation of acoustic sources with a better resolution in time and in place than any other acoustic system.

The purpose of the noise analysis was to detect faults. Industrial gear units were used. The methods presented make it possible to improve the safety of operation and, consequently, the reliability of monitoring operational capabilities.

It is possible to monitor the life cycle of a gear unit in a more reliable way by using appropriate spectrogram samples and a clear presentation of the pulsation of individual frequency components; in addition to the average spectrum, they represent a criterion for assessing the condition of a gear unit.

In concern to life cycle design, an adequate method or criterion can make it possible to monitor the actual condition of a device and its vital component parts, which can have a considerable impact upon the operational capability. By timely detection of faults and damages, it is possible to control the reliability of operation to a great extent. Increased reliability of methods for faults detection improves the prediction of the remaining life cycle of a gear unit.

References

Christensen, J.; Hald, J. (2004): *Beamforming*, B&K technical reviev 1.

Hald, J. (2005): *Combined NAH and Beamforming Using the Same Array*, B&K technical reviev 1.

Heinz, G. (2004): *Locating Noise Sources, A Comparison Between Different Noise LocalizationTechniques*, GFaI Report 001-06-21.

Fellner, W. (2004): Die Akustische kamera, Eine revolutionäre Lösung zum Orten Schallemissionen, Newsletter für professionelle schall und schwingungmesstechnik, Nr.7/2004, Wien.

Belsak, A. (2004): *Razvoj sistema za odkrivanje napak zobniškega gonila*, Master's Thesis, University of Maribor, Faculty of Mechanical Engineringng.

Buch, A. (1998): *Fatigue Strength Calculation*, Trans Tech Publications.

Fladrin, P. (1999): *Time-Frequency/Time-Scale Analysis*, Academic Press.

Mertins, A. (1999): *Signal Analysis*, John Wiley & Sons Inc., New York.

Derrek, S.J. (1999): *Gear Noise and Vibration*, Marcel Dekker.

Suresh, S. (1998): *Fatigue of Materials*, Cambridge University Press.