

STUDYING THE ACOUSTIC EMISSION OF THE TEMPOROMANDIBULAR JOINT

W. LIS, R. SALAMON

Department of Acoustics
Technical University of Gdańsk
(80-052 Gdańsk, ul. G. Narutowicza 11/12, Poland)
e-mail: wall@eti.pg.gda.pl

J. ZIENKIEWICZ

Department and Clinic of Maxillofacial Surgery
Medical Academy in Gdańsk
(ul. Dębinki 7, Poland)

The method of acoustic emission is widely used for testing the strength of materials and in passive underwater acoustics. Recently in the field of medicine, acoustic emission signals received in the traditional phonendoscope method are recorded and processed using advanced electronic technology. Presented in this paper is an example of this work. It is a system that tests the acoustic emission of the temporomandibular joint which when in a pathological state seriously impairs important physiological functions of man. The presented system receives and records acoustic signals emitted by the joint. This is synchronised with the registration of the jaw displacement. Based on that, parameters and characteristics of acoustic emission signals which could indicate a specific disease of the joint are determined. In the research to date the focus has been on determining the statistical distributions of root-mean-square and maximal values of the signals and the current spectrums linked to the movement of the mandible. Clinical tests carried out at the Clinic of Maxillofacial Surgery at the Medical Academy of Gdańsk have provided preliminary confirmation of the usefulness of the system for diagnostic functions. The tests are being continued and are systematically contributing to the collection of signals and cases. This in turn is the condition of progress of continued work on the use of acoustic emission in diagnosing the temporomandibular joint.

1. Introduction

The phenomenon of acoustic emission is widely used in science and technology, in particular for testing the strength of materials and in passive underwater acoustics. For many years now attempts have been made to put this phenomenon to work in medical diagnosing. The research focuses on those sounds emitted by the human body which the physician cannot hear directly because of their volume or high frequency or which he disregards on grounds of interpretative problems. These sounds include acoustic signals

which are produced by the movement of the joints. One of such joints that the medical world shows special interest in is the temporomandibular joint. What sets it apart from other joints is its complex anatomic structure and its exceptional susceptibility to injury plus the intense suffering it causes to the patients once dysfunctional.

The first mention on the use of the acoustic emission of the temporomandibular joint that the authors know of comes from D. WATT [11] who observed the correlation between the nature of audible sounds generated by the joint and malocclusion. The first application of technical means (a microphone and graphic recorder) for the purpose of testing the joint's acoustic emission was described by E. WEGGEN and K.H. GUNTHER [12], and soon afterwards by J. and Z. KRASZEWSKY in Poland [5]. Further work in this area was aimed at improving the technology of sound recording, and in particular the methods of processing acoustic emission signals. The mid eighties saw the beginning of a widespread use of digital and computer technologies in this area. The mainstream works include those of L. HEFFEZ and D. BLAUSTEIN [4] (spectral analysis using the FFT method), L. CHRISTENSEN [2] (statistical methods) and R. BADWAL [1] (fractal method). It was probably because of the high hopes scientists had in the processing of signals that the problem of sensors for the reception of these signals has been disregarded, as well as, although not entirely, the issue of correlation between the signals emitted and the movements of the joint (CH. OSTER *et al.* used X rays to do that [9]).

Systematic research on the acoustic emission of the temporomandibular joint was begun in 1994 at the Department and Clinic of Maxillofacial Surgery at the Medical Academy of Gdańsk and the Department of Acoustics at the Technical University of Gdańsk [6, 13]. The research covered the development of a special sensor for the reception of the signals emitted by the joint [6], design of a system to record and process these signals and clinical testing on a large group of patients. The article will present the design of the system, signal processing methods used and the results of the clinical testing to date.

2. Design of the system

The system for examining the acoustic emission of the temporomandibular joint consists of two channels, as shown in Fig. 1.

The first (acoustic) channel receives and records acoustic signals emitted by the joint, the second measures mandible displacement. Acoustic signals emitted by the joint are transformed into electric signals in a specially designed piezoceramic transducer [6]. The electric signal from the transducer goes through an amplifier and a low-pass filter of upper cut-off frequency of about 10 kHz, and next is sampled at a frequency of 22050 Hz in a 16 bit analogue to digital converter. This converter is a component of a computer stereo audio card. The recorded files are processed and analysed in the computer, mainly using the MATLAB 5-3 programme. The calibration generator is switched on to replace the transducer in order to test and adjust the system's parameters periodically.

The second channel registers the state of jaw opening. To do that a tensometric sensor is used, coupled through a lever with the movements of the jaw (mandible) of the

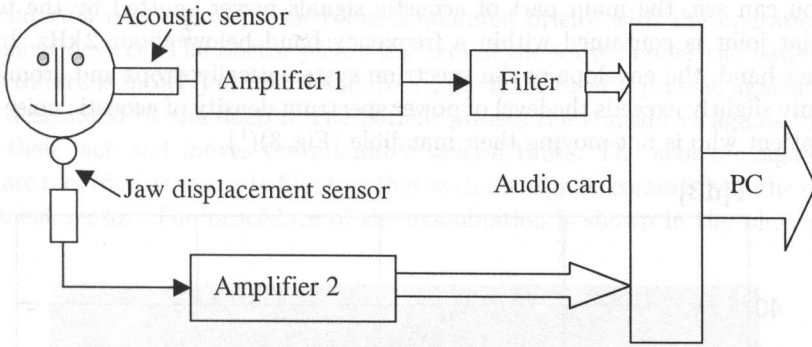


Fig. 1. Block diagram of the system for examining the acoustic emission of the temporomandibular joint.

patient. The electric signal coming from the sensor is amplified and given to the input of the second channel of the stereo audio card. Sampling of this signal is also done at a frequency of 22050 Hz, and the resulting digital signal is recorded synchronously with the acoustic signal in computer memory.

The transfer bandwidth of the acoustic channel was chosen based on the available literature on the spectrum width of signals emitted by the temporomandibular joint [3, 4] and on our own measurements of the spectrum. To take the measurements we used a transducer with upper cut-off frequency of 25 kHz, a broad-band amplifier and an A/D converter with sampling frequency of 41100 Hz. A typical power spectrum density F of a digital signal generated in this way is shown in Fig. 2.

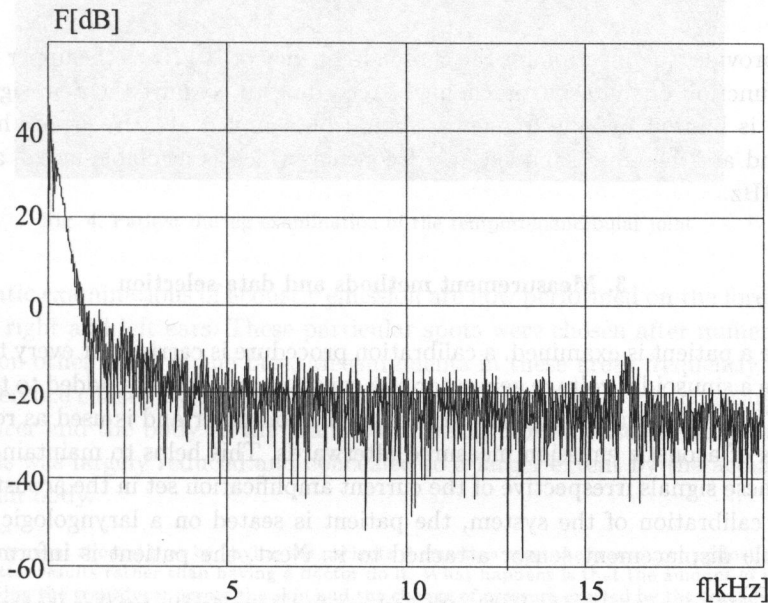


Fig. 2. Typical power spectrum density of an acoustic emission signal.

As you can see, the main part of acoustic signals power emitted by the temporomandibular joint is contained within a frequency band below about 2 kHz. In higher frequencies band, the envelope of the spectrum systematically drops and around about 10 kHz only slightly exceeds the level of power spectrum density of acoustic noise emitted by the patient who is not moving their mandible (Fig. 3)⁽¹⁾.

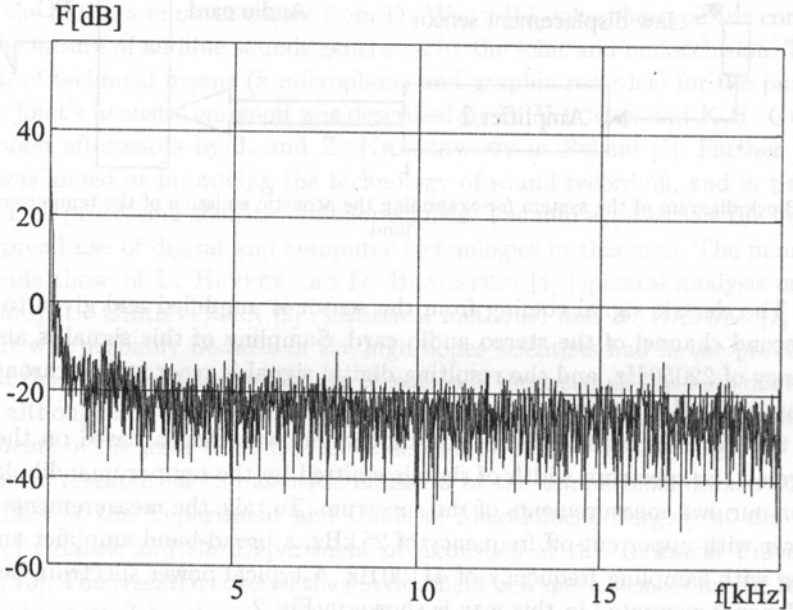


Fig. 3. Spectrum of interference emitted by the patient's body and measurement devices.

This provides justification for the chosen frequency of 10 kHz as the upper limit of the transfer function of the acoustic channel. According to Nyquist theorem signals whose spectrum is limited by this frequency should be sampled at a frequency higher than 20 kHz and are therefore sampled at a frequency which is available in the audio card, i.e. 22050 Hz.

3. Measurement methods and data selection

Before a patient is examined, a calibration procedure is carried out every time. In the procedure a sinusoidal voltage generator of a constant amplitude is added to the acoustic channel. The calibration signal is recorded in the computer and is used as reference for all signals of acoustic emission measured afterwards. This helps to maintain a constant scale of these signals irrespective of the current amplification set in the acoustic channel.

After calibration of the system, the patient is seated on a laryngologic chair with a mandible displacement sensor attached to it. Next, the patient is informed on how

⁽¹⁾ The level of electric noise generated by the machines used is significantly less than the observed acoustic noise.

the examination is going to proceed and acquainted briefly with the operation of the measurement devices. The doctor places the arm of the sensor under the patient's chin and puts the transducer⁽²⁾ in their hand. Next, the transducer is pressed against areas of the face designated by the doctor. The patient presses the transducer against a specific spot on their face and moves the mandible several times. The acoustic signals being emitted are recorded as separate files together with the signals coming from the mandible displacement sensor. The procedure of the examination is shown in the photograph in Fig. 4.



Fig. 4. Patient during examination of the temporomandibular joint.

Systematic examinations of acoustic emission are now performed on the forehead and around the right and left ears. These particular spots were chosen after numerous tests performed on other parts of the face. Measurements in these areas frequently carried a lot of interference caused by the fact that it is difficult to maintain in a constant contact the transducer and the body as the mandible is being moved. Also the level of noise of these signals was largely reduced and concealed to a larger extent by the acoustic noise of the human body.

⁽²⁾ The experiment showed that by having the patients themselves press the transducer against the selected spots gives better results rather than having a doctor do it. What happens is that the amount of interference caused by moving the transducer across the skin and the change of pressure exerted by the transducer against the body is reduced. In general, one can say that the patient has a better control of the examination, can select the transducer's pressure against their body easier and performs fewer unnecessary moves.

Typical signals recorded in one spot that the transducer is placed against are shown in Fig. 5.

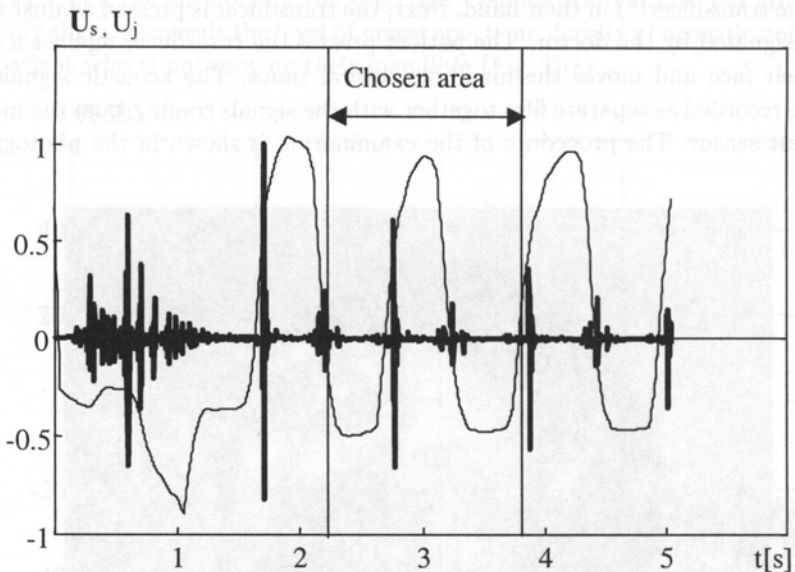


Fig. 5. Acoustic emission signal (thick line) against the signal from the mandible displacement sensor. (U_s - acoustic signal, U_j - relative value of jaw displacement).

The signal coming from the mandible displacement sensor encompasses four cycles of opening and closing of the mouth. Its minimal value is for a closed mouth while the maximal value signifies a full opening of the mandible. In the background of this signal, the signal of the acoustic emission of the temporomandibular joint is clear. It exhibits characteristic short lasting "pulses" of high values and other more equal fragments of smaller amplitudes.

This type of signal presentation has the enormous advantage of allowing each fragment of the acoustic emission signals to be linked to the current phase of mandible opening. When the doctor is interpreting the recorded signals (including the results of the processing), he can easily determine at which point of mandible movement specific acoustic signals are emitted.

Observation of acoustic emission signals and of mandible movement makes the following findings possible:

- in an acoustic emission signal some elements are repeated in some of the opening and closing cycles of the mandible,
- the movement of the mandible in the consecutive cycles is not identical,
- the full amplitude of the mandible movement gives strong acoustic emission,
- the intensity of acoustic emission depends on how quickly the mandible moves observed as a slope of the curve which describes the mandible's path.

These observations lead to the conclusion that from the entire recording we can select the most interesting fragments or at best one fragment which gives the most complete

insight into the joint's acoustic emission. A fragment representative of the phenomenon should include the whole cycle of mandible movement — from the closed state through full opening to a repeated closure. In the fragment chosen, the mandible movement should be complete, quick and possibly uniform. It is the role of the operator to get the patient to perform movements like these. The choice of the appropriate fragment is made subjectively by the doctor based on an overview of all the signals recorded.

The need for selection of the recorded signals is also the result of the need to limit the number of measurement data. The effective time of examining one patient lasts a few dozen seconds which given the relatively high sampling frequency provides more than 2 million samples as the end result of the examination. Looking through such files is very time consuming and occupies a large portion of computer memory. As an example Fig. 6 shows the result of a signal selection from a single measurement point made by the doctor.

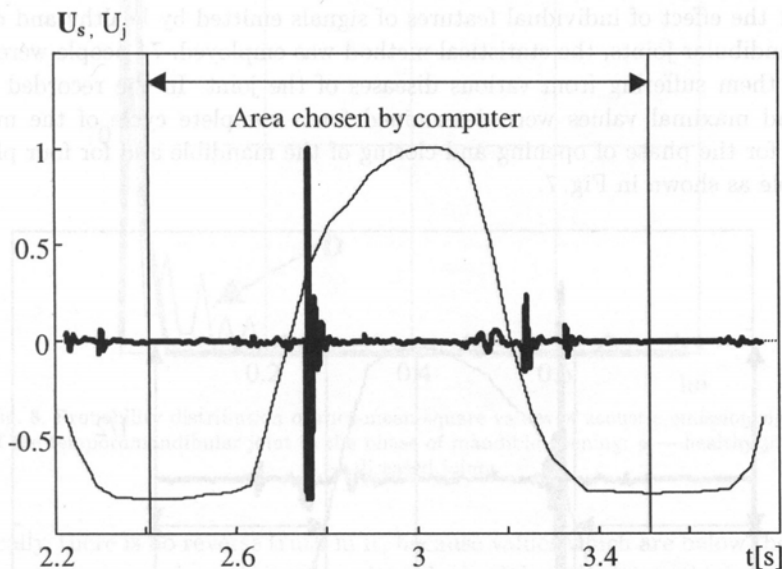


Fig. 6. Fragment of the signal from Fig. 5 chosen by the doctor with one cycle of mandible movement marked, automatically chosen by the computer.

Next, the computer programme determines the accurate limits of the selected fragment starting from the closed state of the mandible to its maximal opening and repeated closure. In this way, the selected signals are saved in computer memory as archive data and used for various analyses which primarily aim at determining the type of pathological state of the joint.

4. Analysis of the acoustic emission signal in the time domain

The literature as well as our own experiments show a lot of discrepancy observed in the signals emitted by the temporomandibular joint in healthy as well as in sick patients.

This is due to the differences in the anatomic structure of the joint and the surrounding osseous and muscular system, pathological states and lack of a complete repeatability of the results of the measurements. For this reason, one cannot expect to obtain a model acoustic emission signal, characteristic of specific diseases or of a healthy joint. The only thing an analysis of acoustic emission signals can do is help to select some characteristic features which can be linked to specific illnesses with a certain degree of probability.

The first step in this direction is to identify those features of signals which will help to distinguish between signals emitted by healthy joints and those emitted by diseased joints. In a recently started new stage of the research, the project concentrates on identifying features that are characteristic of certain pathological states. The results of an analysis of acoustic emission signals presented further on come from the first stage of the research only, because the material gathered on the basis of clinical tests to date is insufficient and does not allow the formulation of conclusions on the particular illnesses.

To limit the effect of individual features of signals emitted by healthy and diseased temporomandibular joints, the statistical method was employed. 74 people were tested, with 33 of them suffering from various diseases of the joint. In the recorded signals, effective and maximal values were determined for a complete cycle of the mandible movement, for the phase of opening and closing of the mandible and for four phases of the mandible as shown in Fig. 7.

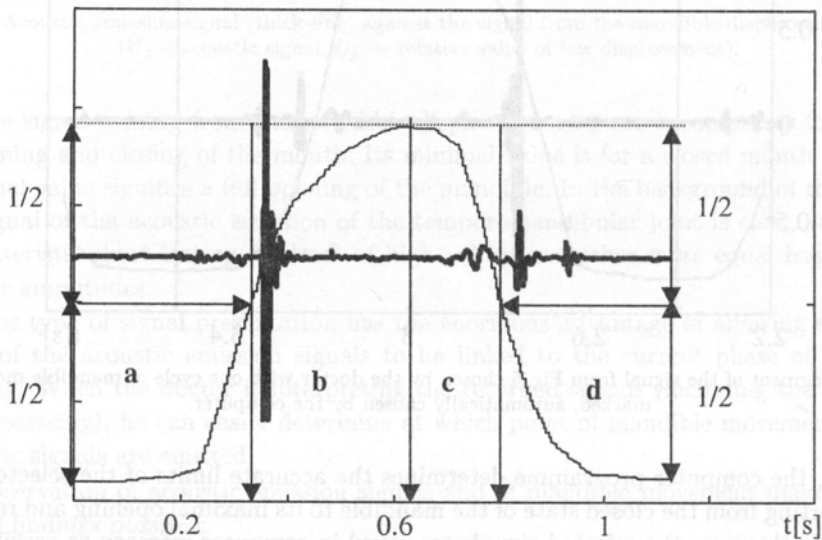


Fig. 7. Phases of mandible movement: a — early opening phase, b — final opening phase, c — early closing phase, d — final closing phase.

The results of the measurements are depicted in the form of probability distribution ϕ of root-mean-square lm and maximal values U for the entire mandible cycle and for its particular phases. From among all the determined probability distributions in the figures given further on, the ones shown are those exhibiting distinct differences between the levels of signals emitted by healthy and diseased joints. The probability distributions

of the root-mean-square value of signals referring to the opening phase of the mandible (Fig. 8) show that when this value exceeds a specific threshold set for the experiment, it is highly likely that the signal comes from a diseased temporomandibular joint.

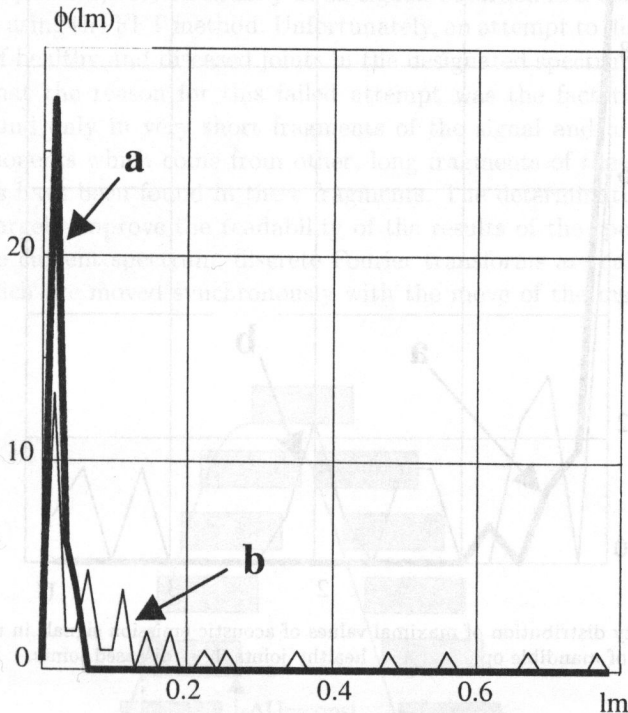


Fig. 8. Probability distribution of root-mean-square values of acoustic emission signals of the temporomandibular joint in the phase of mandible opening: a — healthy joints, b — diseased joints.

Basically, there is no reverse truth in it, because values which are below the threshold are root-mean-square values of signals emitted by both healthy joints (higher probability) and diseased joints (lower probability). A good separation of probability distribution of maximal values of the signals is observed in the second phase of mandible opening. Figure 9 shows clearly that high values of signal maximums in the phase of the mandible's movement are characteristic of diseased temporomandibular joints.

The measurements were used as a basis for determining average values and variances of root-mean-square and maximal values of signals in all the phases of the mandible's movement for both healthy and diseased joints. The results are listed in Table 1 which in clinical practice is used for diagnosing individual cases. The results of measurements taken for each patient are placed in the first column of the table and compared with the mean values obtained during the examination of the 74 people. High dispersions of mean and maximal values make this method of diagnosing unreliable. As a result, other features of the signals have to be found, ones that will provide a better distinction between healthy and diseased joints.

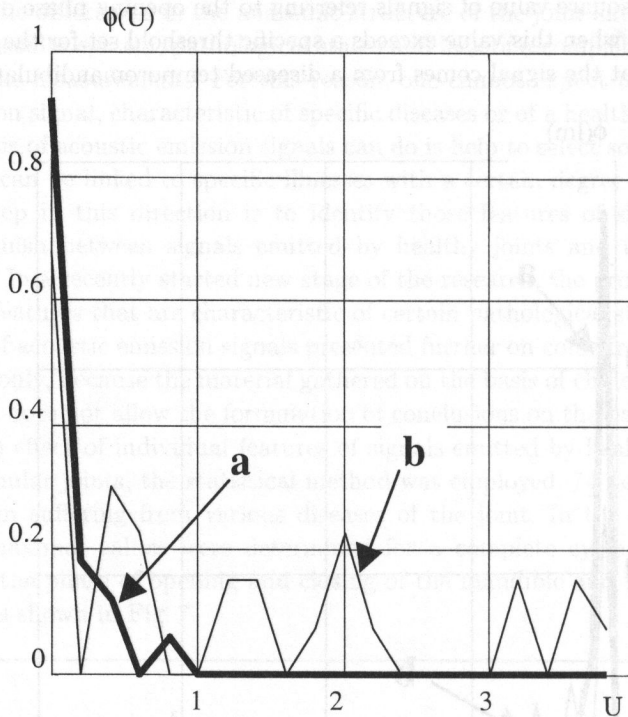


Fig. 9. Probability distribution of maximal values of acoustic emission signals in the final phase of mandible opening: a — healthy joints, b — diseased joints.

Table 1.

Number of examination	023		Full name of patient		
Place of examination	Left ear		Jan Kowalski		
	Result of examination	Sick patients		Healthy patients	
Parameter		Mean value	Dispersion	Mean value	Dispersion
Root-mean square values					
Early opening phase	0.014	0.027	0.040	0.018	0.009
Final opening phase	0.008	0.111	0.225	0.022	0.016
Early closing phase	0.057	0.073	0.116	0.045	0.039
Final closing phase	0.036	0.070	0.101	0.048	0.046
Maximal values					
Early opening phase	0.041	0.164	0.371	0.066	0.052
Final opening phase	0.020	0.611	1.062	0.085	0.117
Early closing phase	0.262	0.461	0.780	0.243	0.278
Final closing phase	0.137	0.301	0.465	0.191	0.196

5. Analysis of signals in the frequency domain

Analysis of acoustic emission signals of the temporomandibular joint began with determining the power spectrum density of all signals recorded in a complete movement of the mandible using the FFT method. Unfortunately, an attempt to distinguish features characteristic of healthy and diseased joints in the designated spectrums failed. Further tests showed that the reason for this failed attempt was the fact that characteristic features are found only in very short fragments of the signal and are masked by the spectrum components which come from other, long fragments of the signal. So far, no specific features have been found in these fragments. The determination of the current spectrum did largely improve the readability of the results of the spectral analysis. In determining the current spectrum, discrete Fourier transforms are calculated in about 80 windows which are moved synchronously with the move of the mandible, as shown in Fig. 10.

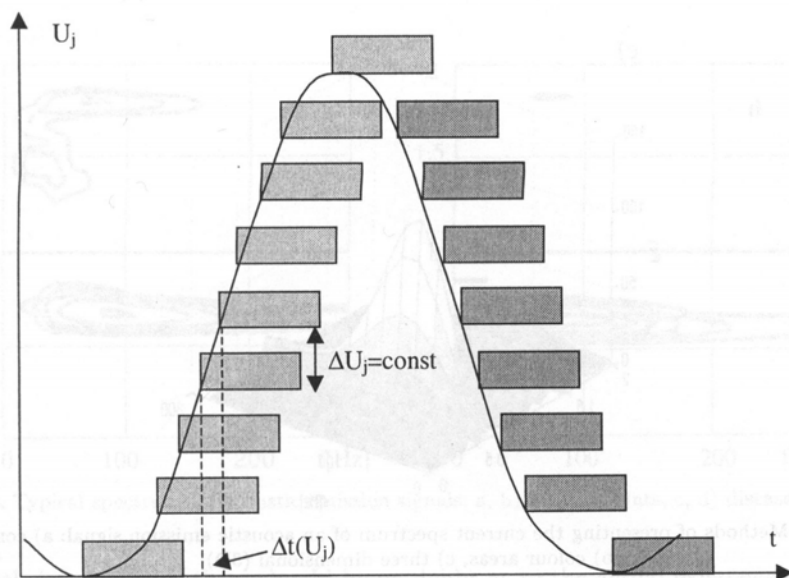


Fig. 10. Illustration of how the window movement is synchronised with the mandible movement.

In each window, the discrete Fourier transform is calculated from 1024 samples of acoustic emission signal. To reduce false spectral lines which are the result of the finite number of samples a typical Blackman window was used [10]. A natural effect of the shortening of the window is a deteriorated frequency resolution which at this point amounts to about 22 Hz. When the entire movement of the mandible was being sampled it amounted to about 1 Hz. Figure 11 shows three ways of presenting the current spectrum used in the system. In the original 12 colours of lines and areas are used to mark the level of the spectrum which greatly facilitates the interpretation of spectrograms. The move of the mandible is described on a scale of 0 to 2 with 0 as the closing of the mandible, 1 — full opening and 2 — repeated closure.

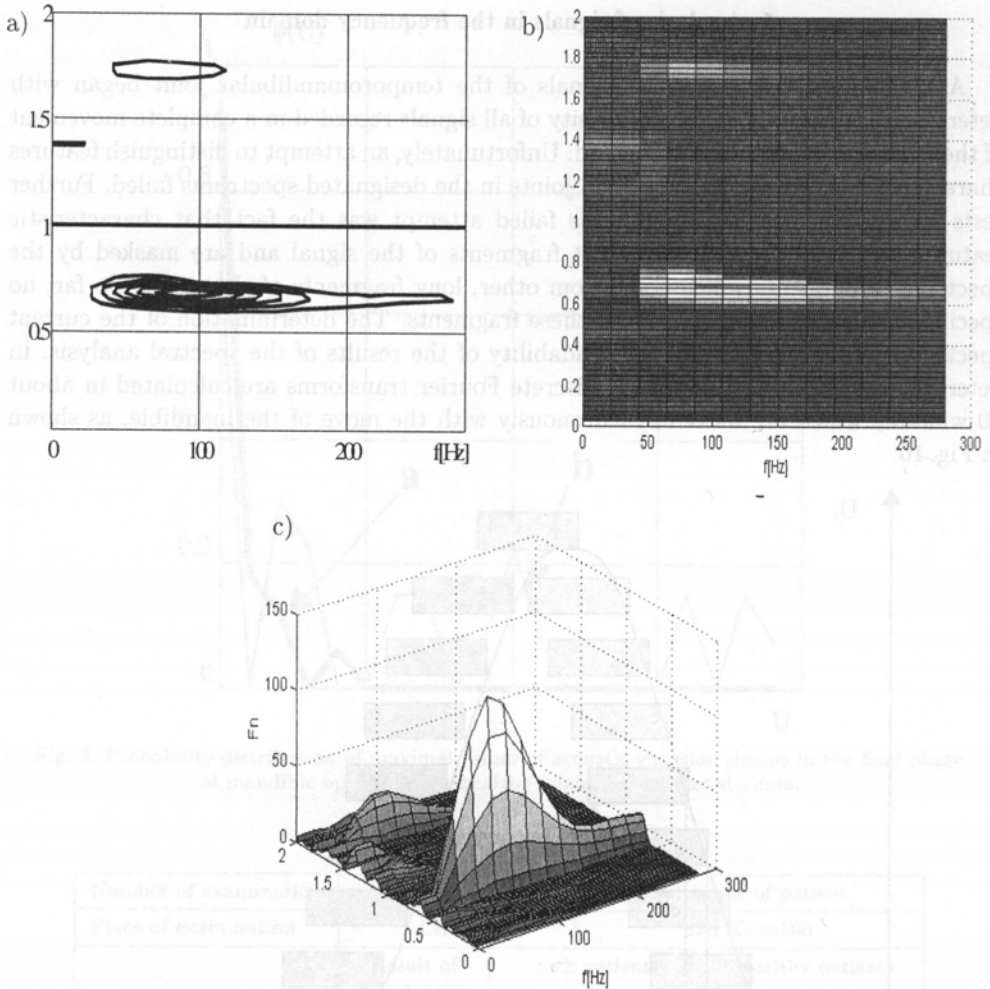


Fig. 11. Methods of presenting the current spectrum of an acoustic emission signal: a) contour, b) colour areas, c) three dimensional (3D).

Following the determination of the spectra of acoustic emission signals of the joints of 74 patients, the spectra were then analysed. The analysis has led to these conclusions:

- the presence of spectrum components exhibiting a high value and a broad band in the phase of mandible opening is typical of numerous pathological states of the temporomandibular joint,
- the presence of spectrum components in the phase of mandible closing only is typical of healthy temporomandibular joints.

Typical spectra of acoustic emission signals of healthy and diseased joints are shown in Fig. 12. The sad thing is that in a few cases of healthy and diseased joints some deviations from these rules were spotted which means that the method cannot be recognised as a valid diagnostic method.

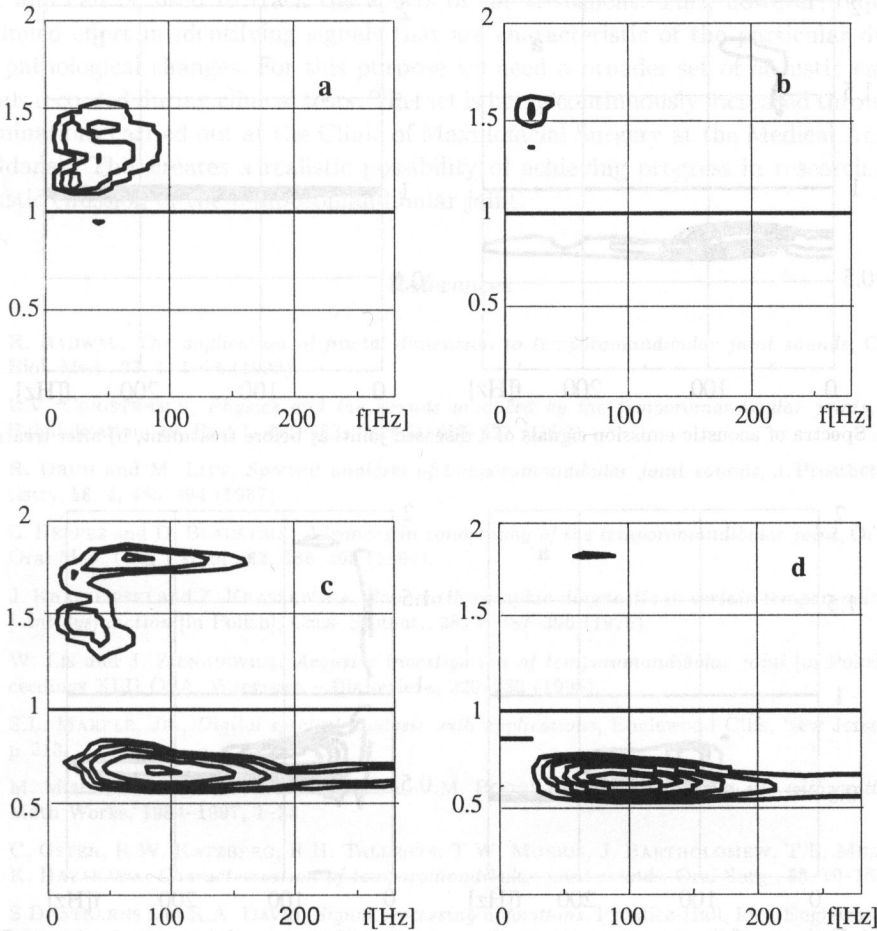


Fig. 12. Typical spectrums of acoustic emission signals: a, b) healthy joints, c, d) diseased joints.

Nonetheless, it seems there should be no doubt as to the actual existence of a correlation between the joint's pathological states and the shape of the spectrum of acoustic emission signals. A proof of that is provided, among other things, by comparing spectrums emitted during the treatment of a diseased joint, shown in Fig. 13. It is true that the shape of the spectrum after a completed treatment continues to be different from one that is typical of healthy joints, however, the features that are characteristic of diseased joints have retreated, too.

The deteriorated resolution following a reduction of the window is especially negative in the range of low frequencies. This can be eliminated though by using one of the parametric methods of spectrum estimation [7]. To illustrate the positive effects of such methods, Fig. 14a shows a spectrum that has been determined using Burg algorithm. This spectrum was calculated on the basis of a number of samples in a window reduced to 64 and assuming a filter model of the 4-th order.

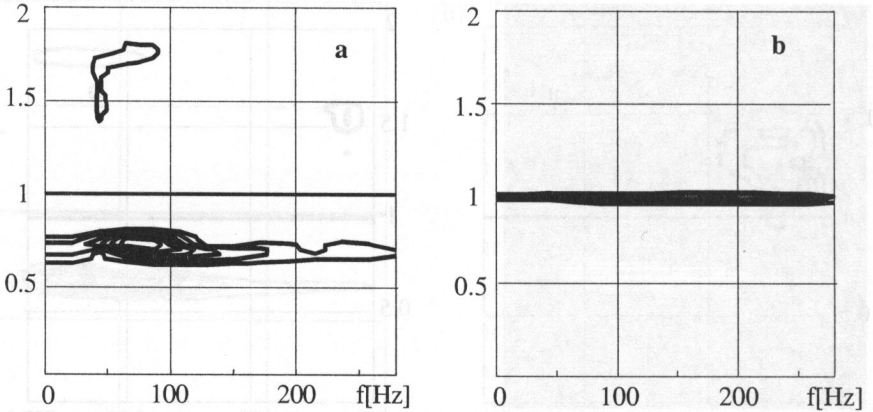


Fig. 13. Spectra of acoustic emission signals of a diseased joint: a) before treatment, b) after treatment.

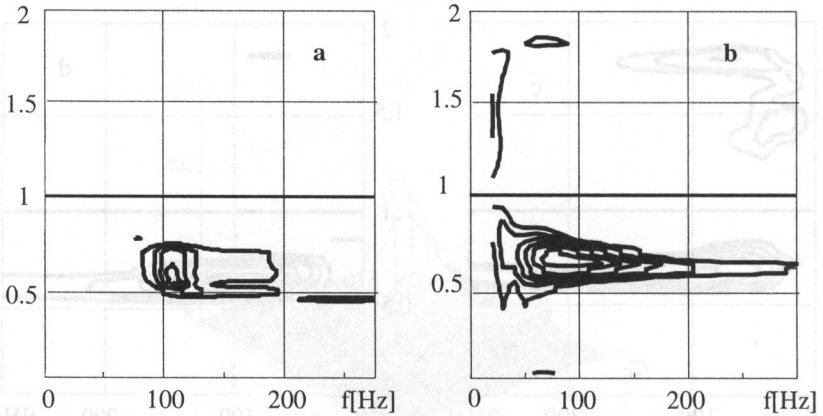


Fig. 14. Estimate of the current spectrum of an acoustic emission signal determined using: a) Burg method, b) wavelet method. (The spectrum of the same signal determined using the FFT method is shown in Fig. 12 d).

Attempts were made to improve the resolution in the time domain (of the mandible movement). To do that wavelet transformation was applied, using Morlet and Coiflet wavelets [8]. The resolution of the current spectrum in the time domain improved only slightly in the range of higher frequencies, as illustrated in Fig. 14 b.

Therefore, "wavelet" transformation can be treated only as a supplement to Fourier transformation with mobile window.

6. Conclusions

The clinical tests to date have shown that analysis of acoustic emission signals can prove a useful tool in the future for diagnosing the diseases of the temporomandibular

joint and can be used to track the effects of the treatment. This, however, requires a continued effort in identifying signals that are characteristic of the particular diseases and pathological changes. For this purpose we need a broader set of acoustic emission signals recorded during clinical tests. This set is being continuously increased through the examinations carried out at the Clinic of Maxillofacial Surgery at the Medical Academy of Gdańsk. This creates a realistic possibility of achieving progress in researching the acoustic emission of the temporomandibular joint.

References

- [1] R. BADWAL, *The application of fractal dimension to temporomandibular joint sounds*, *Comput. Biol. Med.*, **23**, 1, 1-14 (1993).
- [2] L.V. CHRISTENSEN, *Physics and the sounds produced by the temporomandibular joints*, *J. Oral Rehabilitation*, **19**, Part I. 471-483, Part II. 615-627 (1992).
- [3] R. DRUM and M. LITT, *Spectral analysis of temporomandibular joint sounds*, *J. Prosthetic Dentistry*, **58**, 4, 485-494 (1987).
- [4] L. HEFFEZ and D. BLAUSTEIN, *Advances in sonography of the temporomandibular joint*, *Oral Surg. Oral Med. Oral Pathol.*, **62**, 486-495 (1986).
- [5] J. KRASZEWSKI and Z. KRASZEWSKA, *Phonoarthrographic diagnostic in certain temporomandibular joint dysfunction* [in Polish], *Czas. Stomat.*, **28**, 4, 387-396 (1975).
- [6] W. LIS and J. ZIENKIEWICZ, *Acoustic investigation of temporomandibular joint* [in Polish], *Proceedings XLII OSA, Warszawa - Białowieża*, 229-232 (1995).
- [7] S.L. MARPLE, JR., *Digital spectral analysis with applications*, Englewood Cliffs, New Jersey 1987, p. 213.
- [8] M. MISITI, Y. MISITI, G. OPPENHEIM and J.M. POGGI, *Wavelet toolbox for use with matlab*, The Math Works, 1984-1997, 1-33.
- [9] C. OSTER, R.W. KATZBERG, R.H. TALLENTS, T.W. MORRIS, J. BARTHOLOMEW, T.L. MILLER and K. HAYAKAWA, *Characterization of temporomandibular joint sounds*, *Oral Surg.*, **58**, 10-16 (1984).
- [10] S.D. STEARNS and R.A. DAVID, *Signal processing algorithms*, Prentice-Hall, Inc., Englewood Cliffs, New Jersey 1988, p. 167.
- [11] D.M. WATT, *Clinical applications of gnathosonics*, Prosthetic Department, School of Dental Surgery, University of Edinburgh, Scotland, I-II, 16, 83-95 (1966).
- [12] E. WEGGEN and K.H. GUNTHER, *Phonognathographie. Eine Methode zur Registrierung und Beurteilung von Schallphänomenen, die durch den Kaumechanismus hervorgerufen werden*, *Dtsch. Stomat.*, **20**, 575 (1970).
- [13] J. ZIENKIEWICZ and W. LIS W, *A new method of examining phenomena in temporomandibular joint* [in Polish], *Czas. Stom.*, **49**, 10, 710-716 (1996).