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DESIGN OF THE MECHANICAL ANALYZER FOR SIGNAL DECOMPOSITION BASED ON COCHLEA FUNCTION PRINCIPLE

D. Dušek*

Summary: *This paper is concerned with time non-stationary signal decomposition based on the cochlea function principle. The mathematical model of array of resonators is described and also results obtained from this model are presented. The results from mathematical model are also compared with results calculated by Short Time Fourier Transformation.*

1. Introduction

Cochlea is that part of the inner ear where acoustic signals incoming from outer air space are convert to electric signals. Pressure travelling waves in inner ear fluid space are generated by forcing of foot stapes to scala vestibuli. The travelling waves in fluid medium consequently excite also travelling waves on basilar membrane where sense organs are located. From the point of view of mechanics of hearing is very important that locations of the maxima of travelling waves on basilar membrane are frequency dependent. Low frequency tones excite basilar membrane near its apical end. With the increasing of frequency the maxima of travelling waves are moving to the basal end. This effect is caused by varying cross section and following varying longitudinal stiffness of the basilar membrane. The inner ear functions like a mechanical analyzer which is able to decomposes time-nonstationary signals to single frequency components in real time. This principle of inner ear function was verified by experimental measurement „in situ“ on human cadavers (Békésy 1960) or on physical models (Chen 2006) and also by mathematical modelling (Givelberg 2003, Dušek 2004, Nobles 2001).

2. Goal of the work

The cochlea is mechanical analyzer which decomposes input signal into separate frequency components and simultaneously it is filter which pass only frequencies in range from 20Hz to 20kHz.

The goal of this wok will be design of device that working on the cochlea function principle that means device which will be able to decompose whatever non-stationary signal in real time. This device will be designed in relation to possibilities of the MEMS technology.

* Ing. Daniel Dušek, Ph.D.: Institute of Solid Mechanics, Mechatronics and Biomechanics, Faculty of Mechanical Engineering, Brno University of Technology, Technická 2896/2; 616 69 Brno, Czech Republic; tel.: +420 541 142 869; e-mail: dusek@fme.vutbr.cz

One possibility of principle of mechanical analyzer is an array of isolated masses with springs. Different natural frequency will correspond to every mechanical system mass-spring. When the field of isolated masses is actuated, then the masses having their eigenfrequencies same like frequencies included in a forcing signal will start resonating.

3. Mathematical model

The basic principle of the mechanical analyzer is shown on the figure 1. The analyzer is compound for array of resonators and if this array of resonators is actuated by signal which is compound from different frequency components, so only those resonators will vibrate whose eigenfrequencies are equal to frequencies compound in actuated signal.

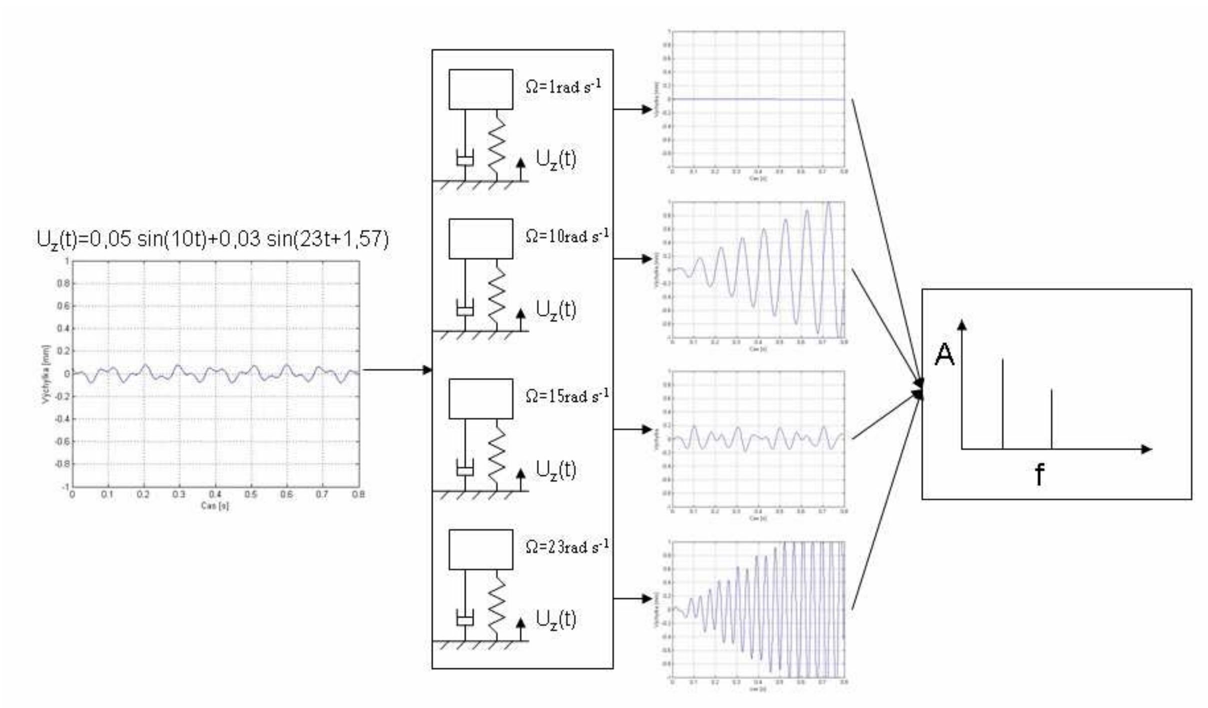

Fig. 1: Principle of signal decomposition based on the array of resonators.

Motion of every resonator can be described by differential equation of second order:

$$m_i \ddot{q}_i + b_i (\dot{q}_i - \dot{q}_z) + k_i (q_i - q_z) = 0, \tag{1}$$

where m_i is mass of *i-th* resonator [kg], b_i is viscous damping of *i-th* resonator [*Ns/m*], k_i is stiffness of *i-th* resonator [*N/m*] , q is displacement [*m*] of mass of *i-th* resonator and q_z is displacement [*m*] of kinematic excitation.

The Eq1. can be rewrited into form :

$$\ddot{q}_i + 2\,\zeta_i\,\Omega_i\,\dot{q}_i + \Omega_i^2\,q_i = b_i\,\dot{q}_z + k_i\,q_z\,, \tag{2}$$

where $\zeta_i = b_i/(2\,(k_i\,m_i)^{0.5})$ is damping ratio and $\Omega_i^2 = k_i/m_i$ is eigenfrequency of the *i-th* resonator. The array of resonators can be simulated by series of calculation for same exciting signal but for different values of stiffness or mass of resonator whereby it can be changed the eigenfrequencies of resonators. Solution of the eq.2 for resonator which is actuated by frequency equal to its eigenfrequency is:

$$Aq_i = (Aq_{zi}\ m_i\ \Omega_i)/ b_i\ , \qquad (3)$$

where Aq_i is amplitude of mass displacement of *i-th* resonator and Aq_{zi} is amplitude of frequency component which is contained in input signal and which is equal to eigenfrequency of the *i-th* resonator.

4. Results

Known test function for verification of the mathematical model was solved first. The test function was sinusoid signal with fluently varying frequency from *40-80 rad/s* (it is *6,4-12,7 Hz*) and may be described by this equation:

$$q_z = Aq_z\ \cos ((\omega\ t) + (a \sin (t))), \qquad (4)$$

where $Aqz=1[m]$ is amplitude of input exciting signal, $\omega=60$ *rad/s* is angular frequency, $a=20$ [-] is constant, $t=0..15$ *s* is time. The parameters of the resonators were following: mass of all resonators was same *m=1kg*, viscous damping was also same for all resonators *b=5 Ns/m*. Stiffness of resonators was varied with value from *400 N/m* to *10000 N/m*.The spectrogram of input test signal calculated by array of resonators is displayed on the figure 2.

The spectrogram of input test signal calculated by Short time Fourier Transformation (STFT) is shown on the figure 3. The parameters for STFT analysis was following: sampling frequency $fs = 100$ *Hz*, length of the signal $N = 1500$ [-], length of the segment window $N_w = 128$ [-], overlap of segments $N_{ov} = 127$ [-]. Comparison of results from STFT and from array of resonators shows that array of resonators give better resolution than the STFT in test signal decomposition.

After verification of mathematical model function was made also analysis of non-stationary signal which is shown on figure 6. This is default signal in Matlab SPTool under name *mtlb*. Total length of this signal is *0.54s* with sampling frequency *fs=7418Hz*.

Spectrogram of *mtlb* non-stationary signal calculated by model of array of resonators is shown on figure 4. The parameters of the resonators were following: mass of all resonators was same *m=1kg*, viscous damping for all resonators *b=50 Ns/m*. Stiffness of resonators was varied with value from 40 k*N/m* to 529000 k*N/m*.

Spectrogram of *mtlb* non-stationary signal calculated by STFT is shown on figure 5. The parameters for STFT analysis was following: sampling frequency $fs = 7418$ *Hz*, length of the signal $N = 4001$ [-], length of the segment window $N_w = 512$ [-], overlap of segments $N_{ov} = 500$ [-].

The figures 4 and 5 show very similar results in signal decomposition. The simulation of array of resonators also showed that it is necessary to use high viscous damping for good signal decomposition.

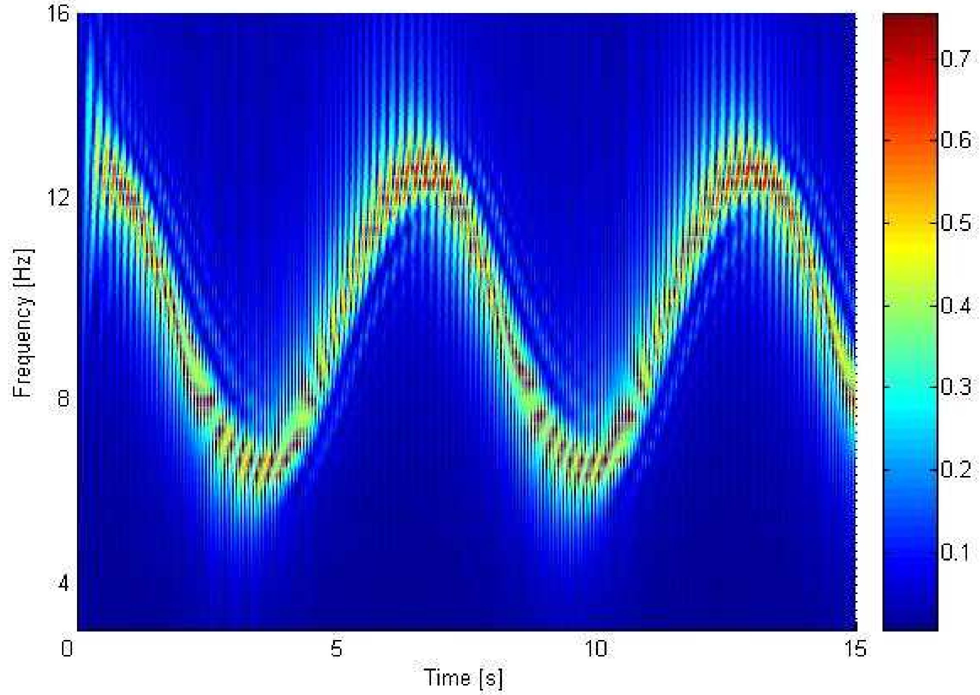

Fig. 2: Spectrogram of input test signal calculated by array of resonators

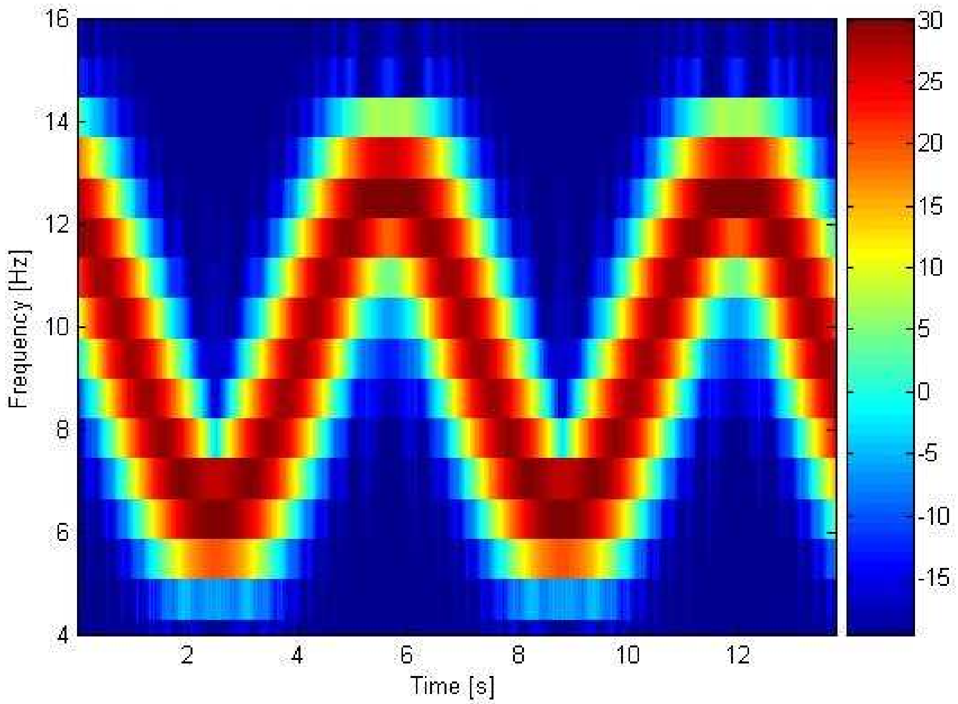

Fig. 3: Spectrogram of input test signal calculated by Short Time Fourier Transformation

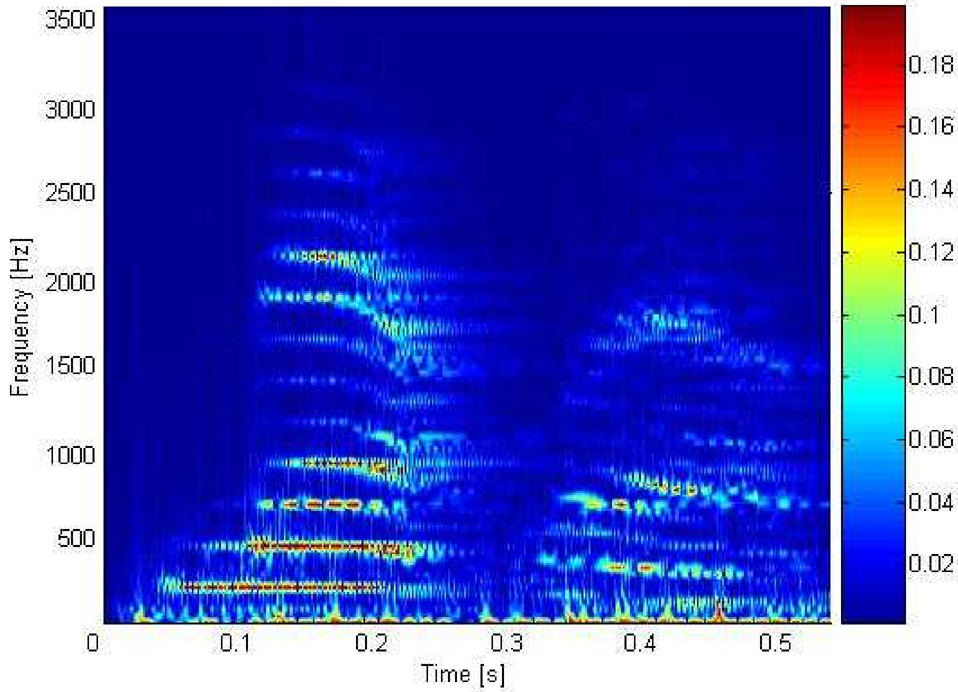

Fig. 4: Spectrogram of input Matlab default signal *mtlb* calculated by array of resonators

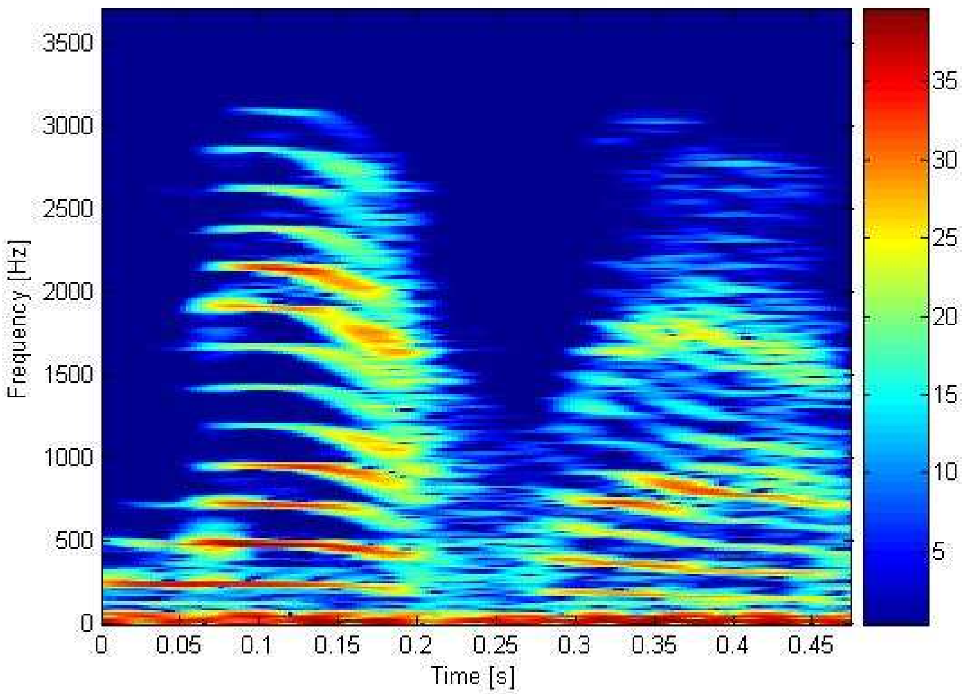

Fig. 5: Spectrogram of input Matlab default signal *mtlb* calculated by Short Time Fourier Transformation

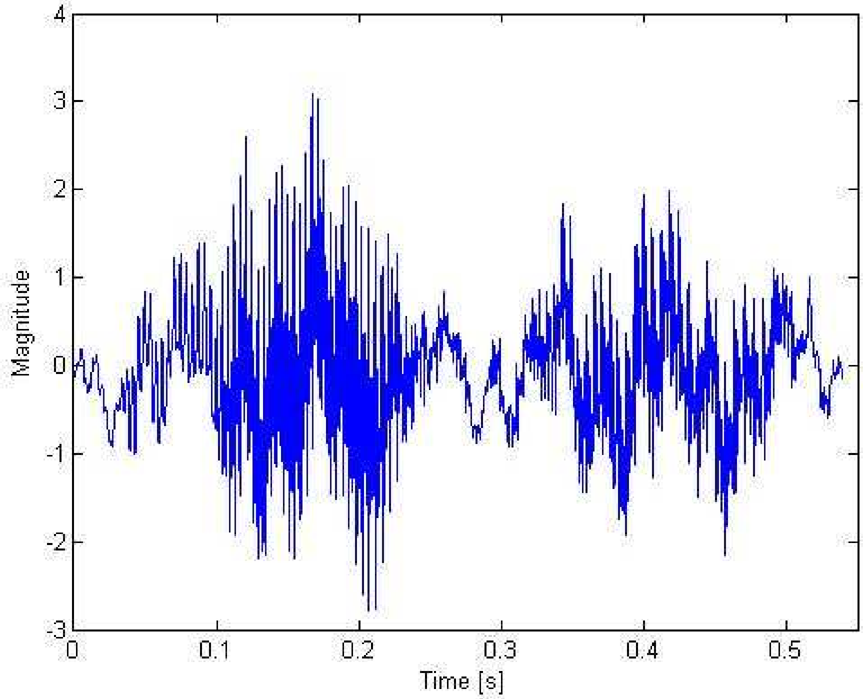

Fig. 6: Analyzed non-stationary default Matlab signal *mtlb*

5. Conclusions

The results of this work should used for design of a mechanical analyzer for real time decomposition of any time-dependent signals based on MEMS technology. Simulation of array of resonators gives very similar results like Short Time Fourier Analysis. Results of simulation of array of resonators also showed that it is necessary to use quite high viscous damping for good signal decomposition.

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