Sound as a mechanical wave

I. Aims of the practical

Getting acquainted with the basic properties of waves. Introducing the relationship between the physical characteristics of sound waves and the sensation of sound. Introducing the basics of the Fourier transform and obtaining the spectra of sounds.

II. Background

A. Mechanical waves

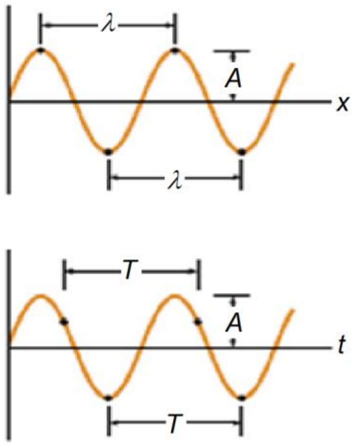
In a mechanical wave, a disturbance propagates in a medium, whilst the particles of the medium oscillate about an equilibrium position. In order to exist, waves need a medium in which a disturbance can be started and a physical process through which the particles of the medium can transmit this disturbance.

The two major types of mechanical waves are

(1) *transverse waves*, in which the particles of the medium move in a direction perpendicular to the direction in which the wave propagates. The wave travelling along a stretched string belongs to this class.

(2) *longitudinal waves*, in which the direction in which the particles of the medium move is parallel to the direction of the propagation of the wave. Sound is a longitudinal wave; the disturbance here is an alternating compression and rarefaction of the medium, that is, a change in the pressure within the medium. In the process of hearing, sound waves make the eardrum oscillate. The ear bones transmit these oscillations to the elliptical window, starting vibrations in the liquid within the cochlea as well. A sound with a given frequency will start a small group of hair cells to oscillate, thus exciting the respective nerve endings which then convey the stimulus to the brain.

B. Physical description of waves



In the figure, we indicated the parameters which describe a wave.

(1) *wavelength (λ):* the smallest distance between two points in the same state of motion.
(2) *amplitude (A)*: the maximum displacement of the particles of the medium from their equilibrium position.
(3) *period (T)*: the shortest time interval that passes between two maxima of oscillations at a given point in space.
(4) *frequency (f)*: the reciprocal of the period.
(5) the *speed v* of a wave is the speed with which the disturbance travels within the medium. This speed depends on the properties of the medium. Eg, the speed of sound is 343 m/s in standard-state air, 1493 m/s in water and 5950 m/s in iron.

The relationships between these quantities are:

$$f = \frac{1}{T}, \quad v = f \cdot \lambda = \frac{\lambda}{T}$$

In a wave, it is not the particles that travel, but the oscillation states and the oscillation energy. To characterise the latter, we define the intensity of the wave as the amount of energy E passing through a unit cross section *q* in unit time *t*. The intensity of a wave is proportional to the square of the oscillation amplitude of the particles, or to the square of the pressure change.

$$I = \frac{E}{q \cdot t} = \frac{1}{2} \cdot \frac{p_{\max}^2}{\rho c} = \frac{1}{2} \rho c A^2 \omega^2$$

C. Sound characteristics

Our senses can distinguish between sounds according to loudness, pitch and timbre. These characteristics correspond to the following physical properties.

(1) *Pitch* depends on the frequency: higher pitch means higher frequency.

(2) *Loudness* is related to the intensity of sound waves, which in turn depends on the amplitude of oscillations. The human ear is able to sense sounds in a very broad intensity range (between 10^{-12} W/m^2 and 10^0 W/m^2). To cope with this range, we describe the intensity on a logarithmic scale: the so-called decibel scale. We express the loudness of a sound in terms of the threshold of hearing for a 1000-Hz sound, the intensity of which is $I_0 = 10^{-12} \mathrm{W/m^2}$. The sound level corresponding to a given sound intensity *I*, expressed in decibels, is given by

$$n = 10 \cdot \lg \frac{I}{I_0}.$$

Since intensity is proportional to the square of the pressure, this expression is equivalent to the form

$$n = 10 \cdot \lg \left(\frac{p}{p_0}\right)^2 = 20 \cdot \lg \frac{p}{p_0}. \quad (1)$$

On this scale, the threshold of hearing corresponds to $n = 10 \cdot \lg \frac{10^{-12}\ \mathrm{W/m^2}}{10^{-12}\ \mathrm{W/m^2}} = 0\ \mathrm{dB}$, whilst the sound level for the threshold of pain is $n = 10 \cdot \lg \frac{10^{0}\ \mathrm{W/m^2}}{10^{-12}\ \mathrm{W/m^2}} = 120\ \mathrm{dB}$. Loudness (sensation, subjective) depends on the intensity (stimulus, objective) and also on the frequency (see Figure 1).

(3) *Timbre* is determined by the frequency and the relative amplitude of the harmonics that are present in the sound in addition to the fundamental frequency. The function which characterises the frequencies and the relative amplitudes of harmonics is called the spectrum, and it can be obtained through the mathematical operation called the Fourier transform.

D. Fourier transform

A time-dependent signal can be expressed as a sum of sine oscillations. If the signal is periodic, the so-called *Fourier components* of the signal are the harmonics corresponding to the period (see Figure 2). For arbitrary (not necessarily periodic) functions, we use the *Fourier transform* to obtain the components. The spectrum of a signal tells us the magnitude and the relative phase of the harmonic components.

Most sound waves are not pure sines. Figure 3 shows examples of the spectra and time-domain waveforms of different sounds.

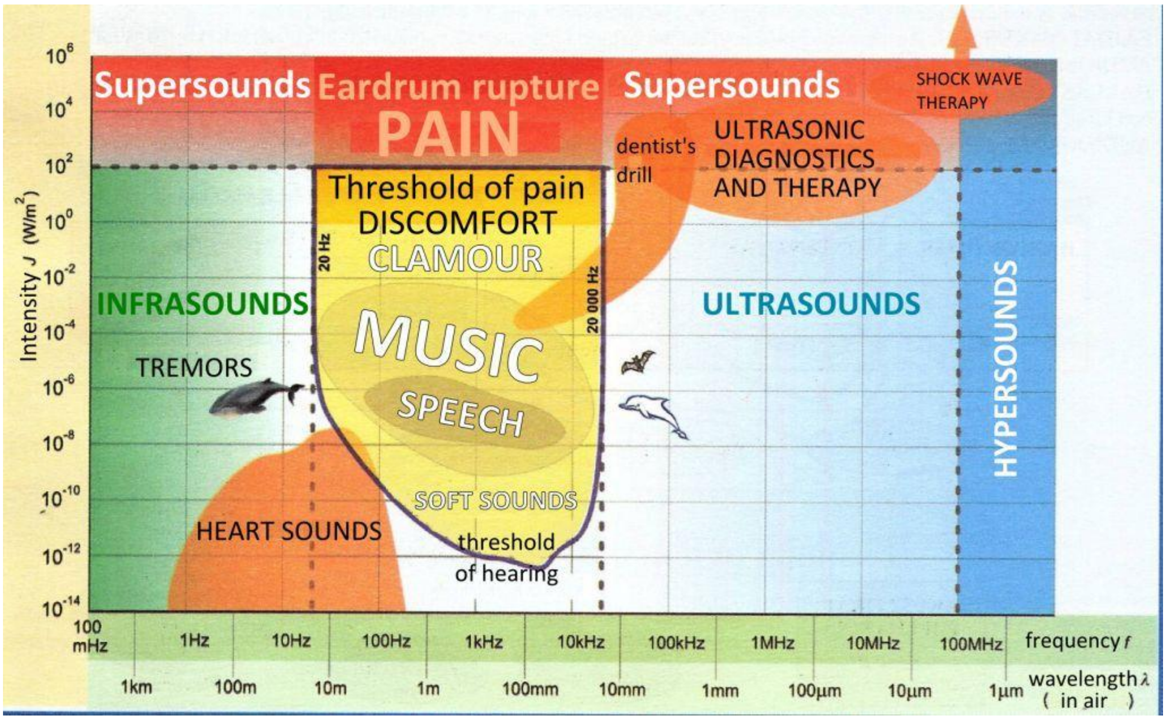


Figure 1. The dependence of loudness on sound intensity and frequency.

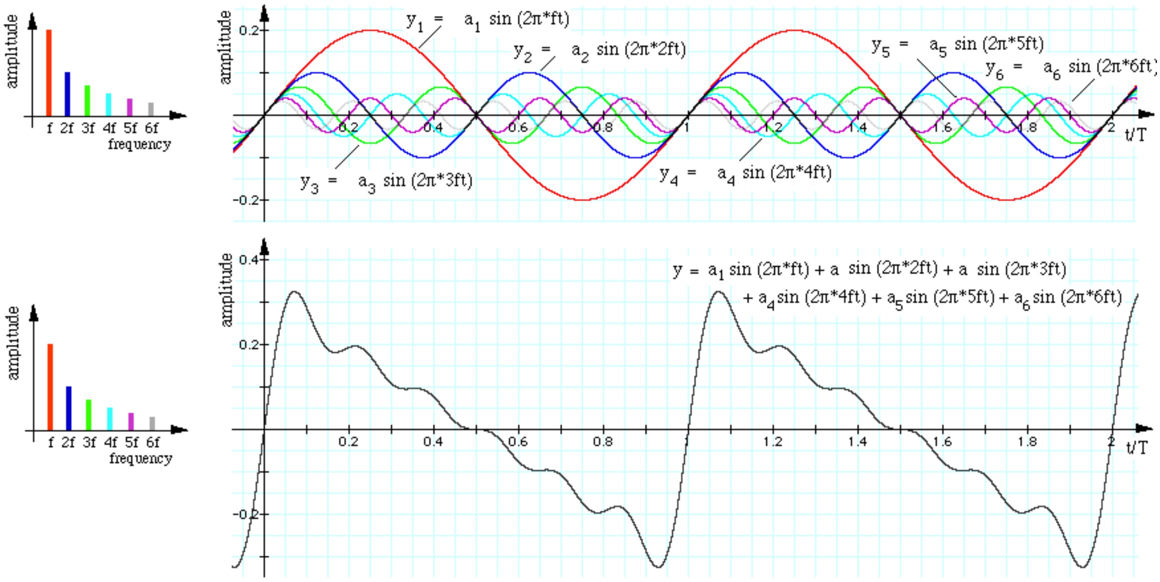


Figure 2. Fourier analysis: decomposition of a periodic signal into sine components.

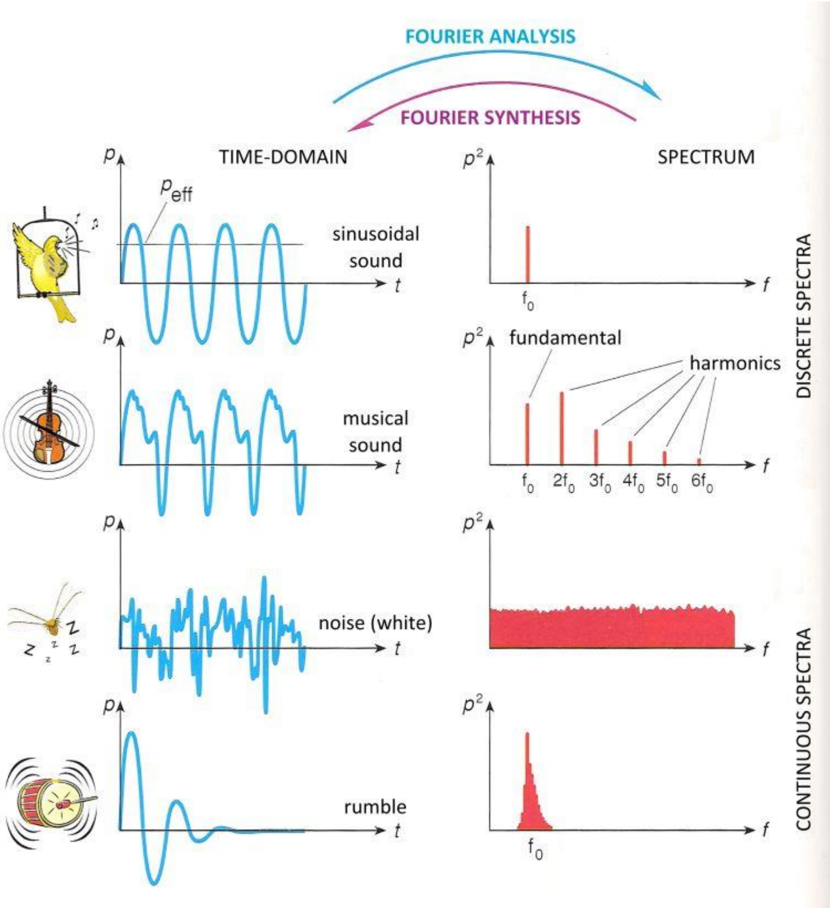


Figure 3. Time-domain waveforms and spectra of different sounds.

III. Tasks

First open the lab report, then start the BSL Pro program and open the recording *AKU-*.acq* to analyse.

A. Time-domain investigations

In the intervals indicated in Figure 4: (1) only tuning fork 1 can be heard; (2) both tuning forks can be heard; (3) only tuning fork 2 can be heard; (4) only tuning fork 1 can be heard.

Zooming in on intervals 1 or 3, you can see sine waves (Figure 5). Select 10 periods of a sine wave and determine the period of the wave. Record the value of the period in your report. The frequency is the reciprocal of the period. Record the frequency values as well. Take care of the units (ms, Hz).

When both tuning forks can be heard (interval 2), the waves are added, and we can observe the phenomenon called *beat* (Figure 6). Determine the period and the frequency of the beat (again by selecting 10 beat periods). Record the values in your report. What relationship can you find between beat frequency and the frequencies of the tuning forks?

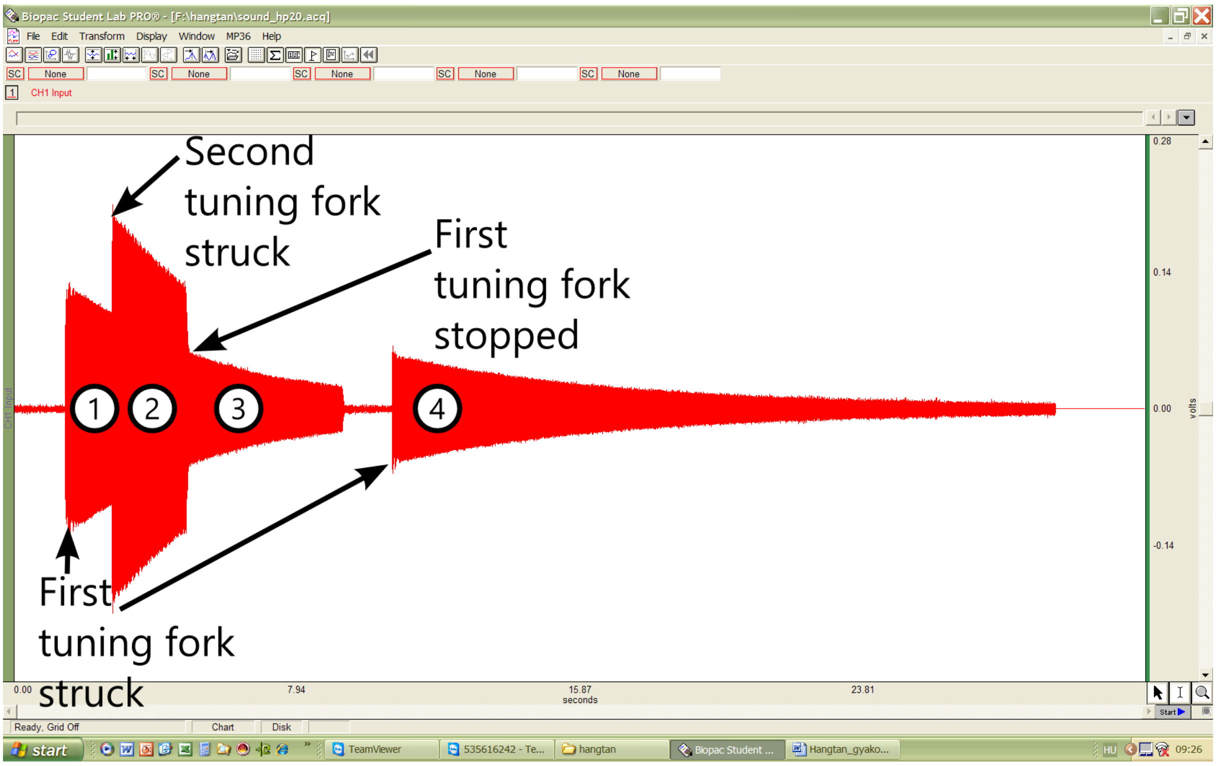


Figure 4. The structure of the recording.

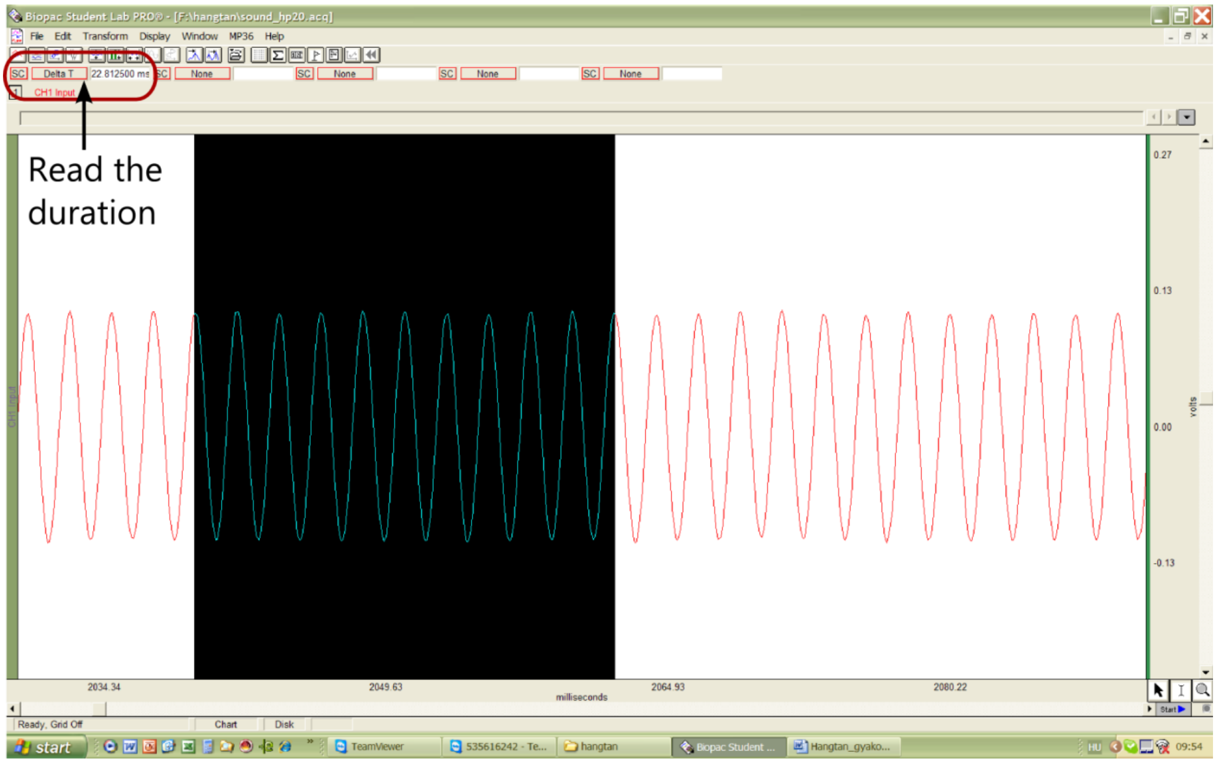


Figure 5. Determining the period.

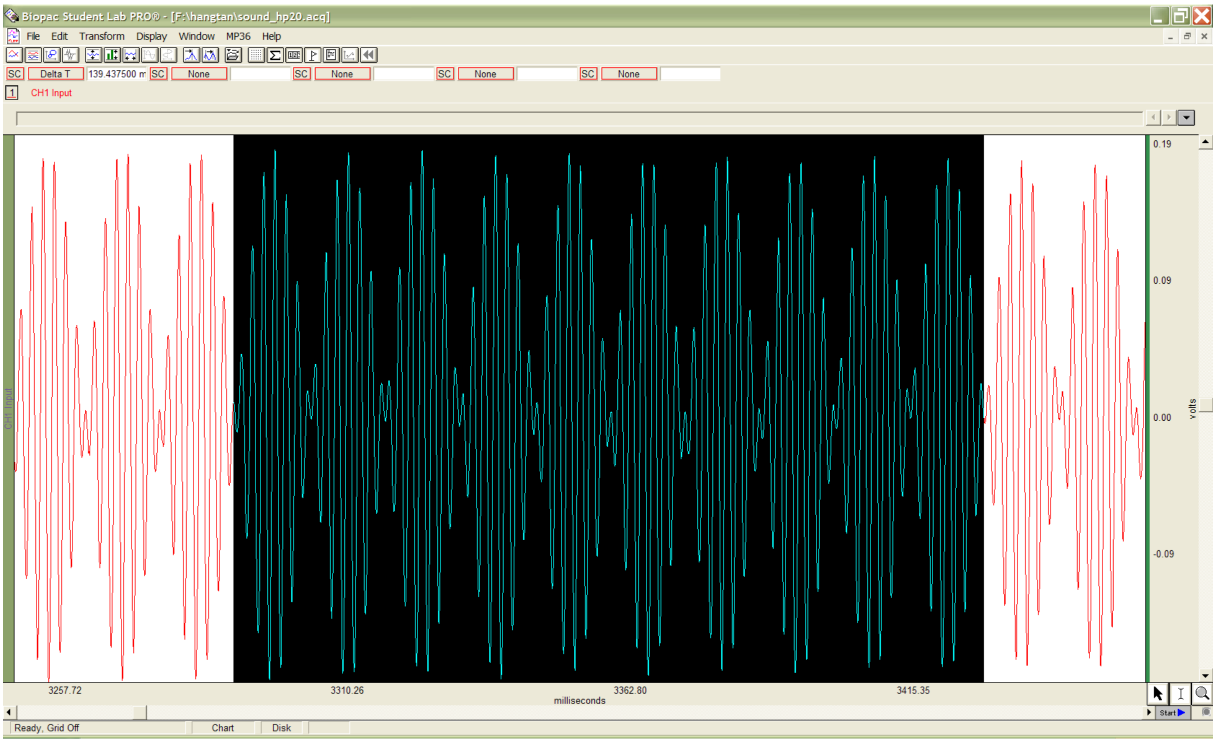


Figure 6. Beats.

B. Spectral investigations (Fourier transform)

We can obtain the spectra (the frequency-component description) of the individual intervals using the Fourier transform (FFT). Select an interval, then use the *Transform » FFT* command to calculate the Fourier transform of the interval (Figure 7). In the pop-up window, select the linear scale option.

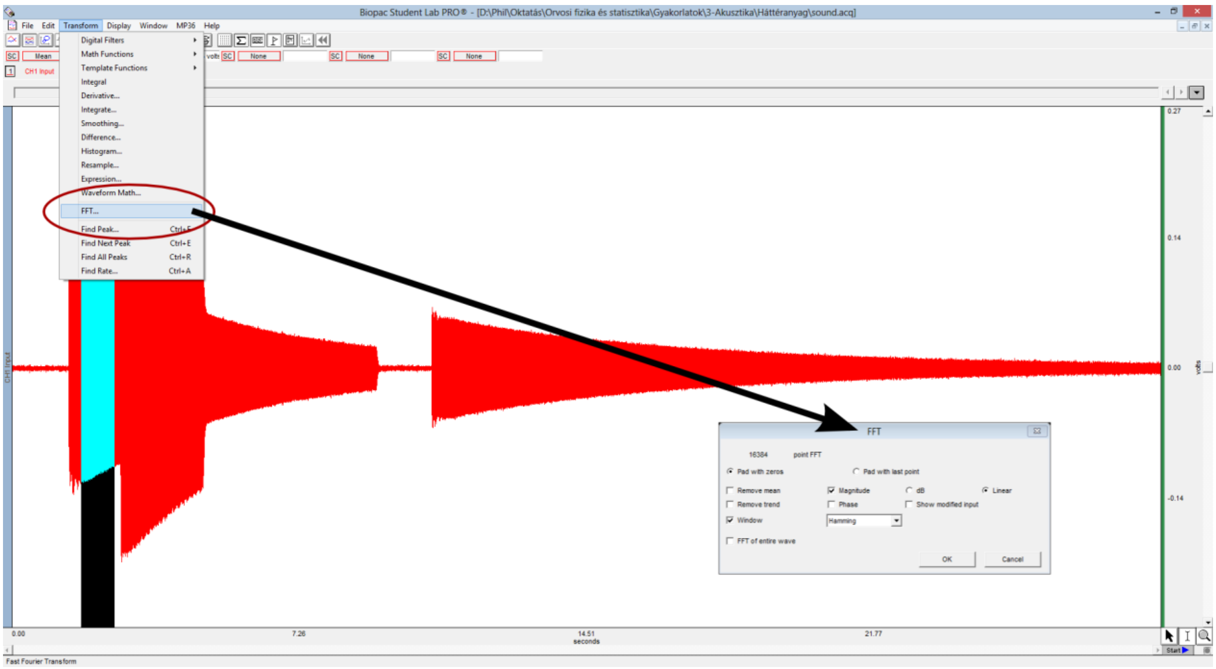


Figure 7. Obtaining the Fourier transform.

You will see a single peak in the spectrum, since one tuning fork can be heard, and thus there is one sine wave present in the sound. Read the frequency at which you can find this maximum (using a measurement window in *F @ Max* mode – see Figure 8) and record the value in your report. Use the same method to examine the spectra of intervals 2 and 3.

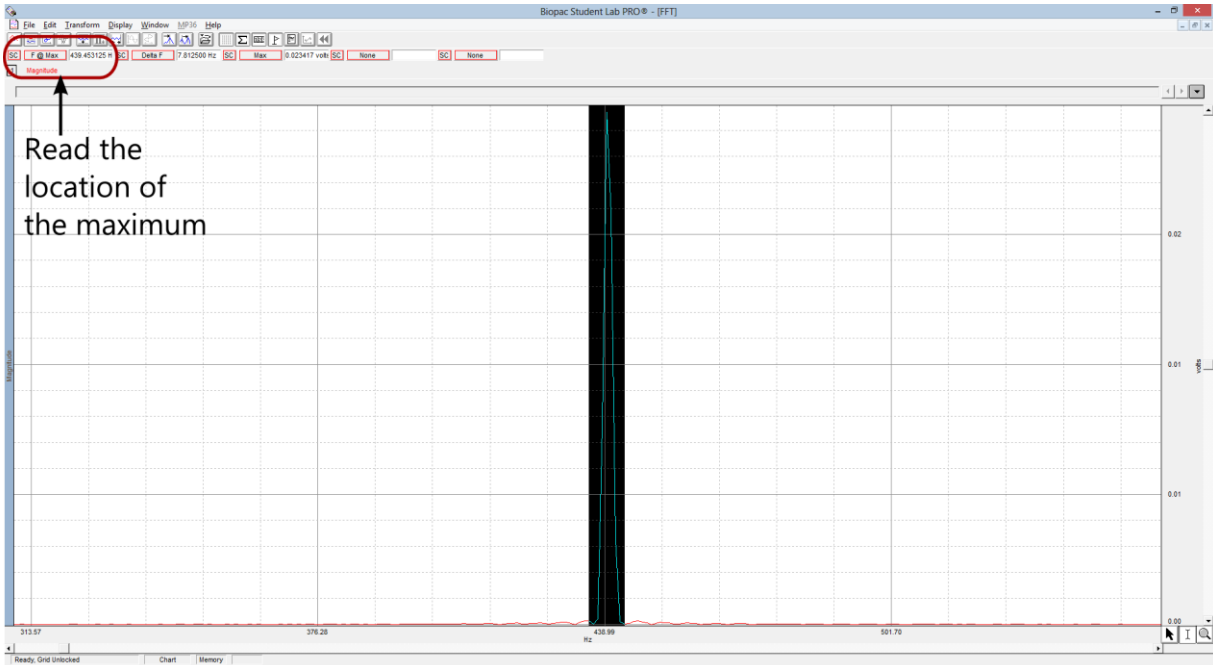


Figure 8. Determining the location of the spectral peak.

The frequency resolution of spectra calculated using the Fourier transform depends on the duration of the measurement. Make two Fourier transforms in interval 4: first with a 0.5-s long section, then with a 10-s long section selected in the time-domain waveform (see Figure 9). Compare the two spectra (see Figure 10). In your report, record the frequency of the peak and the width of the peak for both cases.

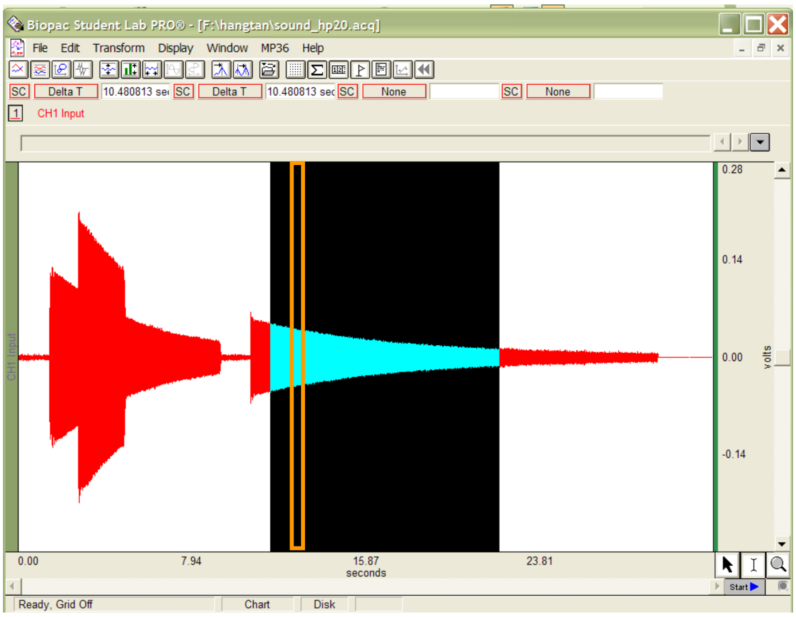


Figure 9. Selecting an interval for the spectrum calculation.

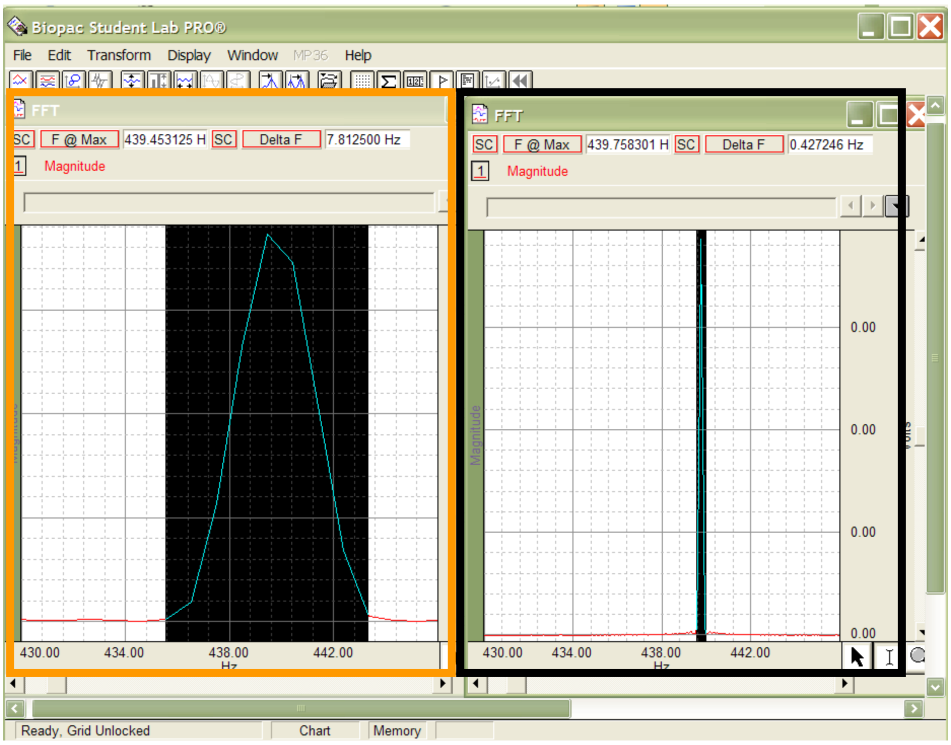


Figure 10. Comparing the spectra obtained from different time-domain interval lengths (0.5 s and 10 s).

C. Investigation of damped oscillations

In interval 4, only tuning fork 1 can be heard. Due to the oscillation's being damped, the intensity of the sound decreases with time. For the next task, we have applied absolute value calculation and smoothing to produce a new channel, channel 2, which contains the envelope of the pressure signal. Channel 3 contains the loudness n, which we calculated from channel 2 using Eq (1) above.

Determine the maximum value (in dB) of the sound level in the damped manoeuvre in channel 3. From the signal in channel 2 (pressure envelope), determine the time required for the amplitude of the sound to decrease to half the original value (Figure 11). What is the decrease in dB that corresponds to the amplitude's being halved? (To answer this question, you can use either the Biopac graphs or the theoretical formula.)

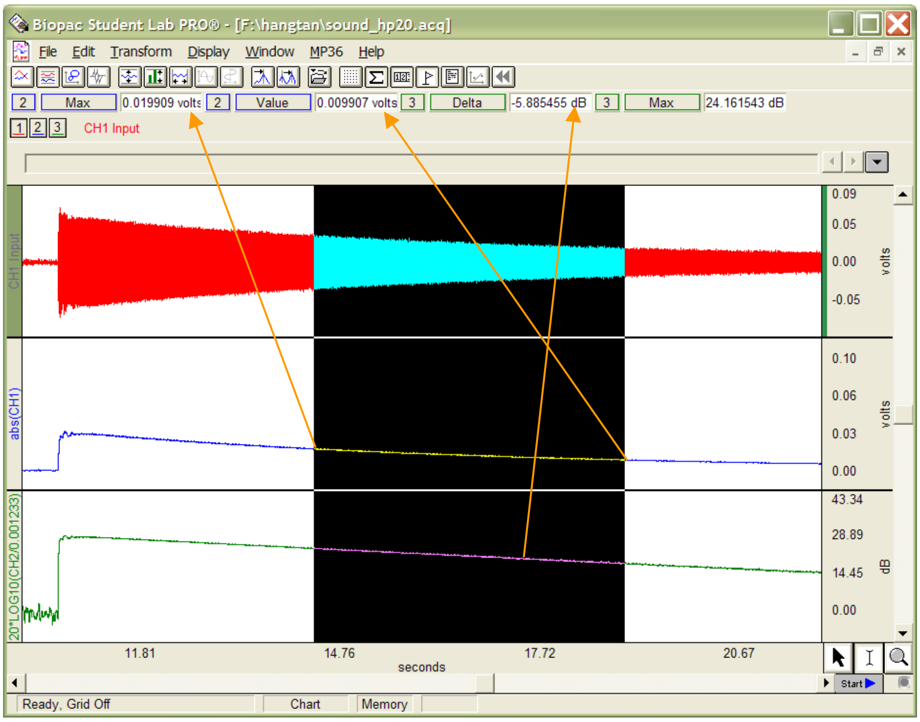


Figure 11. Damping investigations.