Master MIR, semestre 4, examen Microsystèmes Acoustiques

Transducteurs à ondes élastiques

22 January 2021

Duration : 2 hours – You are allowed to use any textbook or lecture notes. Sharing is not allowed. Mobile phones are not allowed.

1 *For Whom The Bell Tolls*

The introduction of Metallica's *For Whom The Bell Tolls*[1] starts with a bell ringing for several seconds. The sound track was recorded and the amplitude of the signal is plotted below in linear scale and dB of the magnitude of the signal (Fig. 1). Because most mechanical systems are anharmonic, the spectrum is complex and shown in Fig. 2.

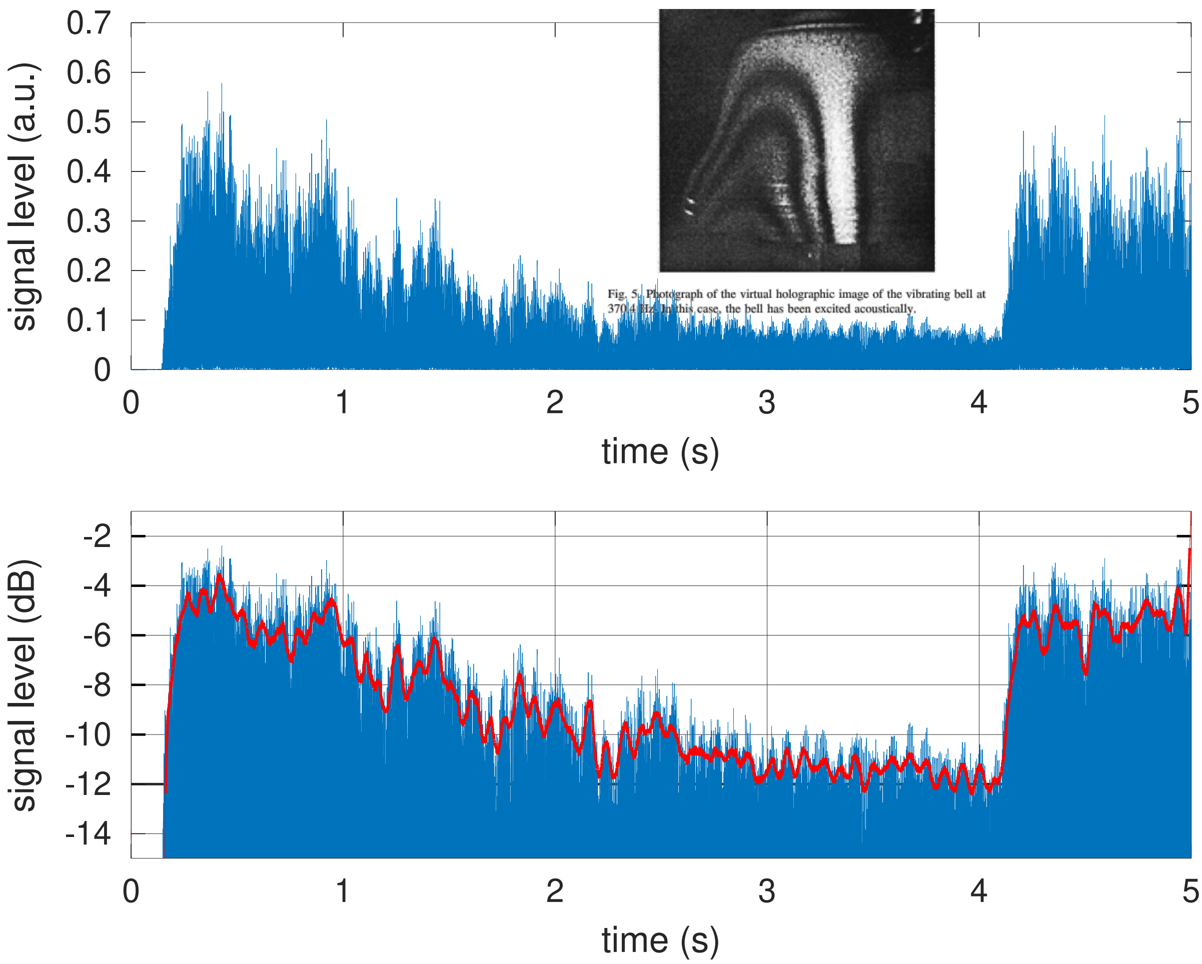

FIGURE 1 – Time-domain evolution of the amplitude, top in linear scale, bottom in dB.

1. https://www.youtube.com/watch?v=eeqGuaAl6Ic

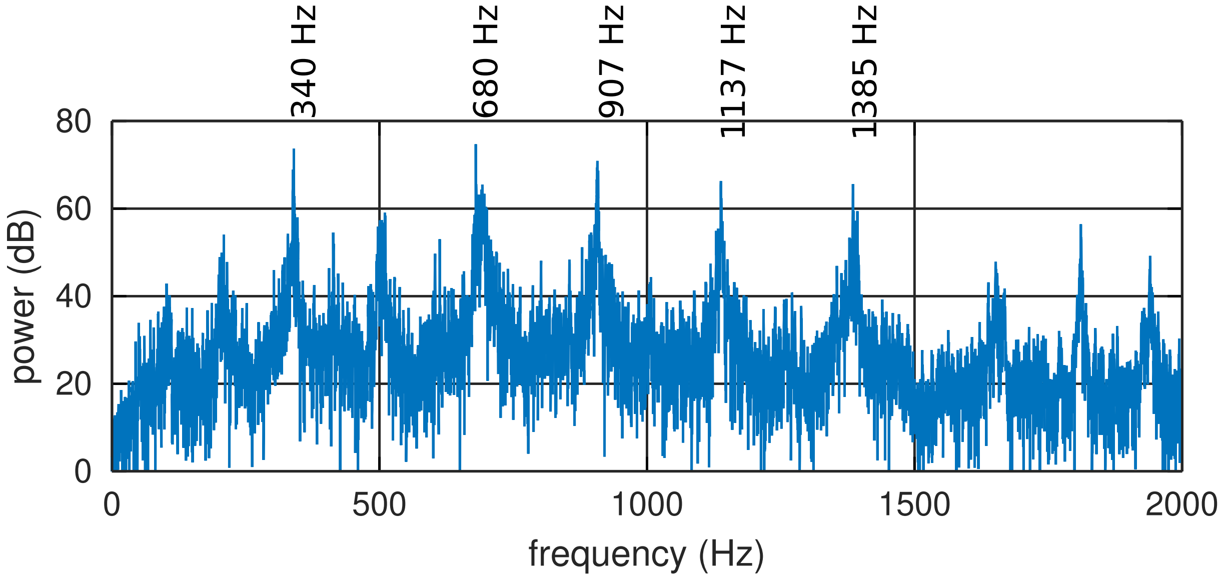

FIGURE 2 – Frequency-domain distribution of power, in dB.

The objective of the analysis is to estimate the quality factor of the structure producing the sound at the introduction of the song.

1. Why is the logarithmic display of the amplitude easier to analyze to extract a quality factor than the linear scale ?

   The exponential decay in a linear scale expressed as $\exp -t/\tau$ becomes in the logarithmic scale $20\log_{10}(e) \times t/\tau$ or a linear decay with slope $20\log_{10}(e)/\tau = 8.7/\tau$. Since $\tau = Q/(\pi f)$ the slope allows to recover the quality factor Q.

2. Estimate the quality factor of the object producing the sound from the available data.

   The signal decays by about 8 dB in about 2.5 seconds so that $\tau \simeq 8/8.7 \times 2.5 = 2.3$ s or a quality factor of $Q = \tau\pi f \simeq 2500$.

3. The spectra are derived from a Fourier transform of the time-series. Would it be possible to deduce the quality factor we just obtained from the width at half height of the derived spectrum ?

   A Q factor of 2500 at 340 Hz means that the width at half height is 0.13 Hz requiring a duration of 7.5 seconds. The record only lasts 4 seconds so that the spectral resolution would be insufficient to deduce the quality factor from a basic spectral analysis.

4. Had we only been given the frequency domain data, what processing step would allow to improve the frequency resolution using signal processing only on the spectrum, as we performed on the correlation peak for subpixel sampling during image processing ? What is the underlying assumption ?

   As we discussed during the sub-pixel analysis of the cross-correlation of the tuning fork motion, we might perform a fit on the spectrum. The most basic approach would be a polynomial fit (Taylor series), the more complex approach would be to fit a physical model of the resonance. In all cases, the assumption is a single resonance not polluted by adjacent modes, i.e. removing the one to one relation between time domain and frequency domain representations.

5. The object producing the sound is not a bell but an anvil (? !) as we are taught in [1]. Considering the Young modulus of steel is about 200 GPa and its density about 8000 kg/m^3, what is the speed of sound in the anvil ? What would be the impact on the sound emitted if replacing steel with brass with a Young modulus of 100 GPa and a density of 8730 kg/m ^{3} ?

   The acoustic wave velocity is the square root of the ratio of the Young modulus to the density or 5000 m/s for steel. Switching to brass, the acoustic velocity becomes 3385 m/s. The lower velocity means that for fixed boundary conditions, the emitted sound will be at lower frequency since the frequency is the ratio of the velocity to the wavelength.

6. Considering the picture of the vibration mode distribution (Fig. 1, top) – the closer the fringes the more energy located in this area of the structure – of the bell and the point at which it is attached, why is the quality factor of this device so much higher than for example that of a clamped beam ?

   As was dicussed in the bulk acoustic resonator geometry and its high quality factor, the acoustic loss beyond the intrinsic material losses is the binding of the vibrating device to the holder. In the case of the bell, we see that the strongest energy concentration is on the ring of the bell with the higher fringe density, whereas the attachement point exhibits low energy density yielding little energy leakage. On the other hand the clamping of the tuning fork is the source of losses despite being far from the largest motion amplitude of the beam as the clamping is the region of highest stress.

7. Bells are usually installed in high towers made of concrete and assembled stones [3]. The tower eigenmodes are excited by the ringing bell. Since concrete and the walls of the tower are made of exhibit high losses, how do the quality factor of the bell Q_{Bell} and of the tower Q_{Tower} combine to provide a global quality factor of the global structure (Remember here the relation of quality factor with loss and remember that loss is the physical quantity that adds) ? Which, of the quality factor of the tower or the bell, drives the global quality factor value, considering the quality factor of the building is typically two orders of magnitude lower than the quality factor of the bell ?

   The quality factor is the ratio of the stored energy to the energy lost per period, so that losses are defined as the inverse of the quality factor. Since losses add, the globale quality factor Q will be given by $\frac{1}{Q} = \frac{1}{Q_{Bell}} + \frac{1}{Q_{Tower}}$. If $Q_{Bell} \gg Q_{Tower}$ or $1/Q_{Bell} \ll 1/Q_{Tower}$ the global quality factor is determined by the tower quality factor or the component with the highest losses in the system.

2 Elasticity and Piezoelectricity

1. In the previous exercise, the elastic properties of the tower and walls are given in terms of Young's modulus and density. Can this be applied to any material ? For example, is this valid for any crystalline solid ? If not, what would be the relevant physical quantities ?
2. What are the material constants required to model the propagation of elastic waves in a piezoelectric solid ? How are they related and how do they impact the physical process of electromechanical energy conversion ?
3. An elastic wave propagates along the [010] direction in a lithium niobate crystal (trigonal symmetry 3m). The elastic constants are given as follows (with c_{ij} in GPa) :
   - $c_{11} = 198$, $c_{12} = 54.7$, $c_{13} = c_{31} = 65.1$, $c_{14} = 78.8$, $c_{33} = 228$, $c_{44} = 59.7$, $c_{44} = 78.8$;
   - $\rho = 4650$ kg/m^3.

   (i) Let us first neglect the piezoelectricity of the substrate. Determine the velocities and polarizations of the three propagating bulk waves.

   (ii) As a general rule, how does piezoelectricity affect the wave propagation properties (e.g. amplitude, frequency, velocity, phase...) ? Write down the expression of the Christoffel's tensor in the case of a piezoelectric substrate.
4. We now consider a surface acoustic wave (SAW) filter based on the use of a pair of interdigitated transducers deposited atop a piezoelectric substrate. We suppose a Rayleigh wave velocity of 3780 m/s. The filter operates at a center frequency of 434 MHz.

   (i) The transducers have a classical geometry, with 2 fingers per wavelength. What is the metal electrode width if the metallization ratio is equal to 0.4 ?

   (ii) This kind of plain filters exhibit insertion losses of at least 6 dB. Can you explain why ? How could these losses be reduced ?
5. SAW filters are extensively used in wireless communications. Knowing that the frequency band of the 4G technology standard goes up to 2.5 GHz and keeping the same velocity value (3780 m/s), what would be the smallest feature of a SAW filter operating for 4G communications ?
6. The 5G technology standard is divided in two frequency bands. The first frequency bands goes up to 6 GHz, the second up to 26 GHz. What are the related electromagnetic wavelengths ? Acoustic wavelength (assuming again a SAW velocity equal to 3780 m/s). Can SAW filters still be considered as a relevant technology ? Can BAW devices be considered relevant ?

Références

[1] K. Grow, *Fighting Fire With Fire : Metallica Look Back on "Ride the Lightning"*, Rolling Stone (2014) at `https://www.rollingstone.com/music/music-news/fighting-fire-with-fire-metallica-look-back-on-ride-the-lightning-243500/`

[2] K. Menou & al., *Holographic study of a vibrating bell : An undergraduate laboratory experiment*, American Journal of Physics **66**, 380 (1998)

[3] R. Smith, H. Hun, *Vibration of bell towers excited by bell ringing – a newapproach to analysis*, Proc. 23rd Int. Conf. on Noise and Vibration Engineering, ISMA **8** 9-152008 (2008) at `http://www2.eng.cam.ac.uk/~hemh1/isma2008.pdf`