In this laboratory, you will perform the simulation of realistic ultrasound images based on an in-house matlab library. It will help you to better understand the main steps involved in the simulation of realistic ultrasound sequences from the probe design to the definition of a dedicated medium.

The lab is divided in three incremental steps:

1. Use of an in-house matlab library called ***pfield*** to get familiar with the transmission part of a physical simulation. During this part, you will generate different transmission schemes (plane wave, diverging wave and focused beam) and observe the influence of key parameters.
2. Use of an in-house matlab library called ***simus*** in order to simulate different numerical phantom, from basic point scatterers to realistic ultrasound images.
3. Use of an open-database recently published by Alessandrini *et al.* [1] to assess the performance of a given tracking method to estimate myocardium motion and strain

This program is ambitious in 1.5 hours! So to allow you to go through all the parts of the lab, most of the matlab code is already in place. You will mostly play with some parameters and equations to implement to study the influence of key aspects in the generation of realistic ultrasound images. The code can be downloaded at the following web-address:

www.biomecardio.com/UFFCschool2019/program.html

The corresponding project is structured as follow:

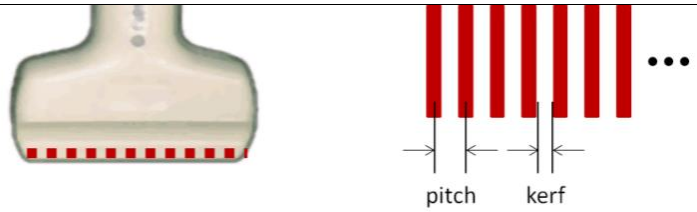
data	Folder containing the data to process. Some examples are already given
help	Folder containing file with the documentation of different key functions
@linear_scan	Folder containing a matlab class to manage a grid where to reconstruct images
papers	Folder containing some articles linked to this session
[*] scripts	Folder containing the different matlab scripts to launch during the lab
src	Folder containing matlab functions to simulate ultrasound images
@us_image	Folder containing a matlab class to manage an ultrasound image

1) Simulation of ultrasound waves from a cardiac probe – Estimated time: 45 minutes

In this session, you will investigate the simulation of an ultrasound beam. In particular, you will analyse how the different properties of the transducer affect the acoustic pressure field.

The code you will use is based on the physics of acoustic waves. In particular, the following conventions/ properties are used:

- the piezoelectric elements are identical and regularly distributed on a line
- The probe contains a finite number of elements (typically 64 or 128)
- the **kerf** and **pitch** parameters characterize the elements of the probe (**cf. Figure 1**)
- The probe emits at a certain **central frequency** (MHz) with a certain **bandwidth** (%) (**cf. Figure 2**)



Prove (in this case linear array) characterized by :

- Number of elements
- Kerf : distance between two elements
- Pitch : distance between two element centres
- Central frequency
- Bandwidth (in %)

Figure 1 – Probe

The elements of the probe are characterized by their *kerf* and *pitch*.

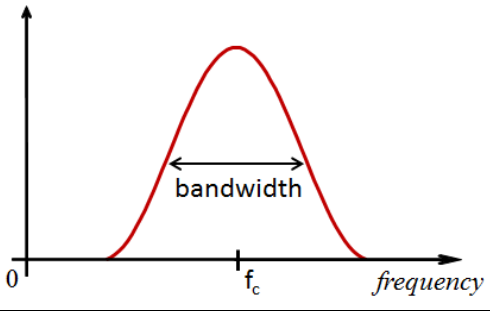


Figure 2 – Emission spectrum

The spectrum of the transmitted signal is characterized by its central frequency (f_c) and its bandwidth (in % of the central frequency)

For this part, you will work on the matlab script named ***script_simulation_part1.m*** present in the folder ***scripts***

At the beginning of this script, you have access to two variables:

1. idPart — variable to select which part of the lab to work on
   - =1 => one firing transmission study
   - =2 => sequence of firings study
2. idTransmission — variable to select the type of transmission to study
   - =1 => plane wave
   - =2 => diverging wave
   - =3 => focus beam

Question 1.1: Launch the code with ***idPart=1*** and ***idTransmission=1***. This code generates an image corresponding to the root mean square of the acoustic pressure field delivered in the medium from the transmission of a plane wave.

Go through the corresponding code and analyse it. You will find all the information of the parameter settings for the key functions in the help folder

Question 1.2: Change part of the code to transmit a plane wave with a tilt angle of 40°. What do you observe?

Divide the probe's pitch by 1.5 and relaunch the code using the same 40 ° tilt angle. What do you see now? What can you conclude?

Question 1.3: Set back the default value of the probe pitch and a 0° tilt angle. You will now study the influence of an apodization applied in transmission. To do so add the following line of code before the computation of delays

```
>> param.TXapodization = hanning(param.Nelements)';
```

Launch the code. What are your observations?

Question 1.4: Launch the code with ***idPart=1*** and ***idTransmission=2***. This code generates an image corresponding to the root mean square of the acoustic pressure field delivered in the medium from the transmission of a diverging wave (**cf. Figure 3**). Change part of the code to change the angular width and the tilt angle of the diverging wave. Generate several examples and observe the impact of such parameters.

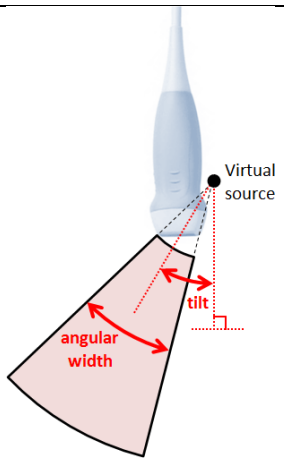


Figure 3 – Diverging wave

For a diverging wave, the delays can be estimated from the angular width (*width parameter*) and the tilt angle (*tilt parameter*).

Question 1.5: Set back the following settings: width=90° and tilt=0° and add an apodization (as in question 1.3). What are your observations?

Question 1.6: Launch the code with ***idPart=1*** and ***idTransmission=3***. This code generates an image corresponding to the root mean square of the acoustic pressure field delivered in the medium from the transmission of a focus beam.

Change part of the code to focus the beam at point (x0,z0)=(2.5,4)cm. What do you see? What can you conclude?

Question 1.7: Launch the code with ***idPart=2*** and ***idTransmission=1***. This code generates a set of images corresponding to the root mean square of the acoustic pressure field delivered in the medium from the transmission of several steered plane wave.

This emission of several firings is classically used to form an ultrasound image. Indeed, the illumination of a medium from the transmission of a set of ultrasound beams will deliver the needed amount of energy to reconstruct ultrasound image with sufficient contrast.

Play with ***idTransmission*** variable to generate sequence of firings for different transmission strategies.

2) Simulation of a realistic ultrasound image – Estimated time: Remaining time :)

In this session, you will investigate the simulation of a realistic ultrasound image. This will be done gradually, from the reconstruction of one point scatterer to a realistic image generated from a template.

The code you will use is based on the convention displayed in **Figure 4**.

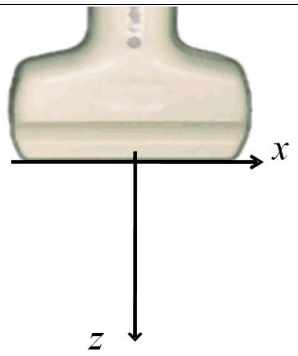


Figure 4 – Coordinate system

The coordinate system with which you will be working is determined by the given figure.

For this part, you will work on the matlab script named ***script_simulation_part2.m*** present in the folder ***scripts***

At the beginning of this script, you have access to two variables:

1. idPart — variable to select which part of the lab to work on
   - =1 => reconstruct one point scatterer
   - =2 => reconstruct speckle in a small ROI
   - =3 => generate realistic numerical phantom
   - =4 => reconstruct a realistic ultrasound image from one firing
   - =5 => reconstruct a realistic ultrasound image from several firings
2. idTransmission — variable to select the type of transmission to study
   - =1 => plane wave
   - =2 => diverging wave
   - =3 => focus beam

Reconstruction of an image from one point scatterer

Question 2.1: Launch the code with ***idPart=1*** and ***idTransmission=1***. This code reconstructs an ultrasound image from a medium composed by one point scatterer from the transmission of one plane wave.

Go through the corresponding code and analyse it. In particular, have a look at the documentation of the functions named *simus*, *rf2iq* and *migrate* present the help folder.

By playing with parameter ***idTransmission***, reconstruct the same medium using different transmission strategy. What do you observe?

Reconstruction of an image from a set of point scatterers

Question 2.2: Launch the code with ***idPart=2*** and ***idTransmission=1***. This code reconstructs an ultrasound image from a medium composed by a set of point scatterers defined through the variable ***N_sca_speckle*** from the transmission of one plane wave.

Go through the corresponding code and analyse it.

Question 2.3: Launch this code by making vary ***N_sca_speckle*** from 1 to 1000 scatterers (*i.e.* 1 / 5/ 10 / 100 / 500 / 1000). What do you observe?

Question 2.4: Run the same experiment but with a diverging wave (***idTransmission=2***) and a focus beam (***idTransmission=3***). What do you see? Can you interpret it?

Generation of a realistic numerical phantom

Question 2.5: Launch the code with ***idPart=3*** and ***idTransmission=1***. This code generates a numerical phantom from a real ultrasound image (defined as the template image). The total number of scatterers is computed from the variable ***bckDensity***. This variable corresponds to the number of scatterers per resolution cell (whose dimensions correspond to the point spread function of the system)

Go through the corresponding code and analyse it.

Question 2.6: The backscattered amplitude attached to each scatterer is computed by default as the intensity I of the template image at the same position. As seen in the presentation of O. Bernard on Monday, this amplitude should be computed as:

$$ampl = 10^{\frac{dB_{range}}{20}\left(\frac{I}{I_{max}}-1\right)} \quad (1)$$

where dB_{range} corresponds to a parameter which controls the dynamic of the amplitudes. We will set the corresponding value to 60 (which fix a dynamic range of 60 dB) in the rest of the lab.

Implement equation (1) and insert it at the correct place in the code. Relaunch the code to save the numerical phantom with the correct amplitudes.

Reconstruction of an ultrasound image from a realistic numerical phantom using one firing

Question 2.7: Launch the code with ***idPart=4*** and ***idTransmission=1***. This code reconstructs an ultrasound image from the medium generated in question 2.6

Go through the corresponding code and analyse it.

Question 2.8: Run the same experiment but with a diverging wave (***idTransmission=2***) and a focus beam (***idTransmission=3***). What do you see? Which emission is the best suited when only one firing is transmitted?

Reconstruction of an ultrasound image from a realistic numerical phantom using several firings

Question 2.9: Launch the code with ***idPart=5*** and ***idTransmission=2***. This code reconstructs an ultrasound image from the medium generated in question 2.6 using a set of diverging waves

Go through the corresponding code and analyse it.

Question 2.10: Run the same experiment but with varying values of number of firings (controlled by the variable ***nbFirings***).

Reference

[1] M. Alessandrini, B. Chakraborty, B. Heyde, O. Bernard, M. De Craene, M. Sermesant and J. D'hooge, "Realistic Vendor-Specific Synthetic Ultrasound Data for Quality Assurance of 2D Speckle Tracking Echocardiography: Simulation Pipeline and Open Access Database.," in IEEE Transactions on Ultrasonics, Ferroelectrics, and Frequency Control*, vol. 65, pp. 411-422, 2018.*