Biomedical Ultrasound Fundamentals of Imaging and Micromachined Transducers

Course Instructor: Prof. Karla P Mercado-Shekhar

Department of Electronic Systems Engineering

Indian Institute of Science, Bangalore

Lecture – 07

In today's lecture, we will introduce different imaging modes in ultrasound. Ultrasound imaging visualizes internal body structures using various imaging modes such as A-mode (amplitude mode), B-mode (brightness mode), M-mode (motion mode), and Doppler mode. The Doppler mode itself has several types including continuous wave, pulse wave, color Doppler, and power Doppler, all of which will be discussed today.

First, let's discuss A-mode, which stands for amplitude mode. A-mode is based on the pulse-echo ultrasound technique and represents the instantaneous echo signal amplitude versus time after the transmission of the ultrasound pulse. As explained previously, a transducer sends ultrasound waves into a tissue composed of layers like fat, muscle, and air. There are acoustic impedance mismatches between the different tissue interfaces, which result in echoes returning to the transducer. The arrival time of these echoes is determined using the range equation: $t = 2 \times d \,/\, c$ where t is the arrival time, d is the distance from the transducer to the interface, and c is the longitudinal speed of sound.

When plotted, the echo amplitude as a function of time shows distinct peaks corresponding to the fat-muscle and muscle-air interfaces. A-mode displays echo data from only a single beamline, which is a limitation of this technique. In the previous lecture, we solved a problem using this concept, where the distances from the transducer to the fat-muscle and muscle-air interfaces were given as 5 mm and 15 mm, respectively. With the speed of sound assumed to be 1540 m/s, we calculated the arrival times of the echoes using the range equation. For the fat-muscle interface at 5 mm (0.005 m), the echo arrived at 6.5 microseconds, while for the muscle-air interface at 15 mm (0.015 m), it arrived at 19.5 microseconds. It’s crucial to pay attention to units during such calculations.

A-mode ultrasound, although not common in general medical diagnosis, is extensively used in ophthalmic ultrasound to measure eye dimensions, particularly in cataract operations. It is also employed in non-destructive testing of structures like railway tracks, aircraft wings, and steel structures, though this is beyond the scope of this class.

Next, we discuss B-mode or brightness mode ultrasound. The B-mode technique involves either a single-element transducer moving laterally to cover the imaging field of view or an array of multiple elements covering a wide range. The transducer sends ultrasound signals towards the tissue of interest, and the echoes are collected and processed to generate the B-mode image. The brightness of these echoes, which forms the B-mode image, is determined by the amplitude of the signal envelope, obtained from the A-mode signal through a process called the Hilbert transform.

A B-mode image is a vertical stack of A-mode lines, creating a two-dimensional image of the tissue cross-section. The brightness in the grayscale image depends on the echo amplitude; a higher echo amplitude results in a brighter appearance. B-mode ultrasound has diverse applications, such as fetal ultrasound, where it visualizes the baby by placing the transducer on the mother's abdomen. In echocardiography, B-mode is used to image the heart. The chambers of the heart appear darker due to the lower scattering of blood compared to the surrounding heart walls.

In B-mode imaging, the echogenicity of structures is discussed, which refers to how bright or dark a structure appears compared to surrounding tissues. Hypoechoic structures are darker, isoechoic structures have similar brightness, and hyperechoic structures are brighter than the surrounding tissues. For example, in an ultrasound phantom, wire targets appear more echogenic (hyperechoic) than the surrounding material. Clinical examples include gallbladder ultrasound, where a stone appears brighter due to its high acoustic impedance compared to the surrounding fluid. Cysts in the prostate, filled with fluid, appear darker (hypoechoic) relative to the surrounding tissue.

If we use a matrix array transducer or a linear or phased array transducer and mechanically scan it across a 3D volume of interest, we obtain what's called 3D ultrasound. If we collect a 3D ultrasound image over time and process it, we get 4D ultrasound, which allows for live imaging. This technique is commonly used today, for instance, to show parents what their baby's face looks like. Additionally, we can observe B-mode ultrasound images of different heart cross-sections and 4D ultrasound images of heart valves, which help in diagnosing valve diseases.

M-mode ultrasound, or motion mode, represents tissue motion over time using B-mode images. It focuses on one lateral location and tracks the echoes from that location over time, depending on the frame rate or pulse repetition frequency of the ultrasound system. Doppler ultrasound, based on the Doppler effect defined by Christian Andreas Doppler, is used to image moving tissues like blood flow. The Doppler effect occurs when a source of waves moves relative to a receiver, resulting in a frequency shift. In ultrasound, this shift helps measure blood flow velocities. For example, when a transducer sends an incident wave at a specific angle to a blood vessel, the frequency of the reflected signal from red blood cells changes due to their movement. This change, the Doppler frequency shift, is used to calculate blood velocity. Various Doppler modes include continuous wave Doppler, which uses two crystals for continuous transmission and reception, allowing accurate flow display without aliasing but causing range ambiguity. Pulse-wave Doppler, using short ultrasound pulses, offers good range resolution but struggles with high velocities and aliasing. Color Doppler provides a 2D image of blood flow using a red and blue color map to indicate flow direction and velocity, such as in the femoral artery and vein. It is also used to examine the carotid artery, which supplies oxygenated blood to the brain. Power Doppler, more sensitive than color Doppler, focuses on intensity rather than direction, enhancing sensitivity to low-velocity blood flow, useful for detecting small blood vessels. In summary, we discussed A-mode ultrasound, which is a one-dimensional signal of the ultrasound echo from tissue; B-mode ultrasound, which stacks A-mode signals to create a 2D image; M-mode ultrasound, used for tissue motion; and Doppler imaging, which maps blood flow. We also covered 3D and 4D ultrasound for time-based tissue motion changes and different Doppler modes, including continuous wave, pulse-wave, color, and power Doppler. We reviewed echogenicity, classifying structures as hyperechoic, hypoechoic, and isoechoic. Future lectures will delve deeper into Doppler ultrasound.