Exercise: Ultrasound signals from moving targets

Aim

To understand how object movement affects the backscattered ultrasound signal. Keywords: Timeshift, phaseshift, Nyquist limit, aliasing, angle dependence.

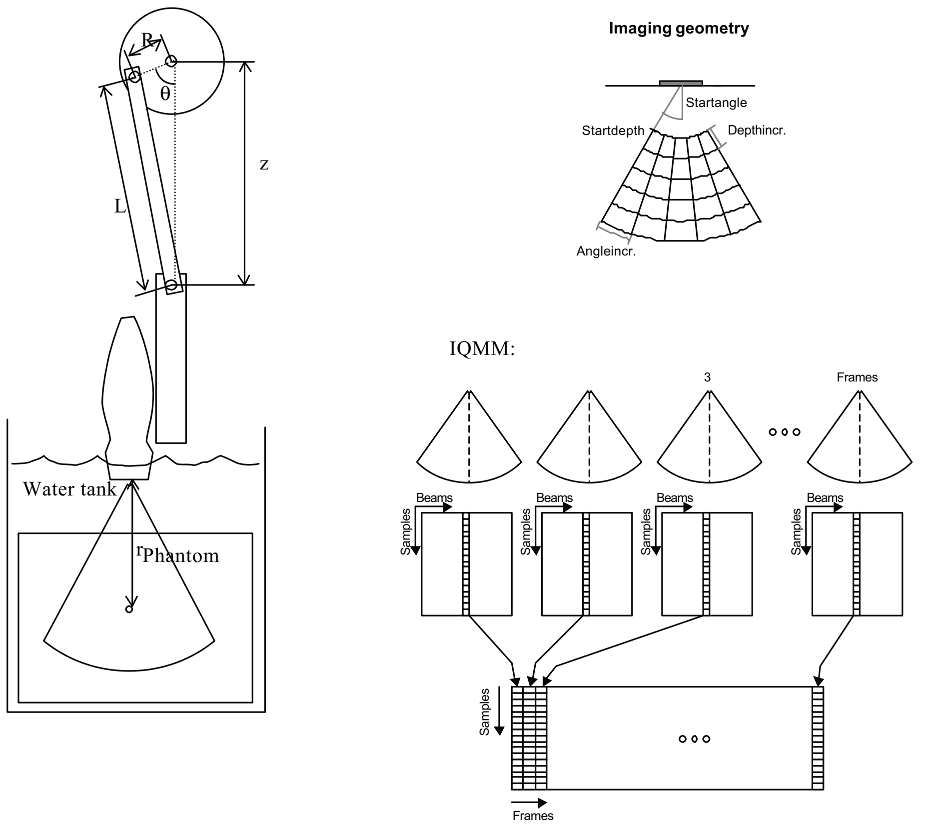

Figure 1: Phantom setup.

Background

IQ-data is aquired with the probe mounted on a motorized piston, as in Figure 1. The IQ-data is aquired at a high frame rate, that is about 350 frames per second. To achieve this high frame rate, the number of transmitted pulses must be reduced, and therefore each image has a limited amount of beams.

Exercises

Part 1: Analytic expression for velocity

Find an expression for z, the stroke length of the piston, as a function of time t, rotation period T, exenter distance R, and piston length L. Use the approximation that $R << L$. Name the time when the piston is at the bottom t0. Find the velocity of the piston.

Name the distance between the point at the middle of the transducer surface and a fixed point in the phantom directly under as r. Write the relation between $r'(t)$ and the velocity of the piston.

Part 2: M-mode

Load IQ data and corresponding settings from the file `slowmotion.mat`, and make a new matrix containing the beam in the middle of the sector from every frame. The data in the 3D IQ matrix is organized as *samples x beams x frames*.

Tip: the matlab function `squeeze` removes singleton dimensions.

Make an M-mode image of this matrix with distance from the probe as y-axis and time along the x-axis. Use logarithmic compression and adjust the gain and dynamic range.

Tip: To make the time axis, you might want to use the frame rate, which is given in the parameter `s.Framerate_fps`. Use `s.iq.DepthIncrementIQ_m` to make the distance axis. The number of beams, samples and frames can be read from the parameters named `s.iq.SamplesIQ`, `s.iq.BeamsIQ` and `s.iq.FramesIQ`.

Estimate the rotation period T, the time t_0, and the exenter distance R from the image. Insert the values into the analytic expression, and plot $r(t)$ on top of the image. $L = 10cm$. How is the calculated movement compared to the observed movement?

Part 3: Timeshift in the RF-data

Plot the analytically calculated $r'(t)$. Choose an image (a frame) where the velocity is approximately one third of the maximum velocity, and take 2 subsequent beams (in time) of IQ-data from the M-mode matrix. Use the analytic expression for the movement to calculate the velocity for this image. Also calculate the radial displacement and expected time shift in the RF-signal.

Convert the two beams of IQ-data to RF-data with a sampling rate of 200 MHz, and plot both beams in the same figure using different color/linetype. Zoom in on a small segment of the signal, and read the timeshift between the pulses in nanoseconds (ns).

Part 4. Cross-correlation and phaseshift in the RF-data

Calculate the cross-correlation $r_{yx}(l)$ between the RF-signals ($x(t)$ and $y(t)$) for l=[-100 100]:

$$r_{yx}(l) = \sum_t [y(t)x(t+l)] \tag{1}$$

Sum from $t = 15000$ to $t = 20000$. Plot $r_{yx}(l)$ as a function of the lag l. At what timeshift does the cross-correlation function achieve its maximum value?

Use the temporal resolution of the RF-signal ($1/200MHz$) and the relation between the two-way distance and time to relate the maximum in $r_{yx}(l)$ to the timeshift and the movement. A timeshift equal to the pulse period $T = 1/f_0$ corresponds to a phaseshift of 2π radians. Calculate the phaseshift in the RF-signal for this image both analytically and for the estimated timeshift.

Part 5. The autocorrelation method.

Use the same two beams of IQ-data as in part 3. Calculate the phaseshift between the pulses using the autocorrelation method:

$$\Delta\theta = \arg\{< x_{iq}(r)^* y_{iq}(r) >\} \tag{2}$$

$\arg\{\dots\}$ means phase angle (`angle` i Matlab) and $*$ means complex conjugate (`conj`). $< \cdots >$ means finding the expectation value. Use averaging (`mean`) of 20 samples near the middle of the beam to find the expectation value.

- Compare with calculated and estimated phaseshift in the RF-data in the previous part.
- Give an expression for the relation between the velocity v, frame rate FR, wavelength λ and the phaseshift in the IQ-signal $\Delta\theta$.
- Estimate the phaseshift for all pairs of neighboring beams in the image sequance. Convert phase shift to velocity, and plot it together with the analytically calculated velocity.

Tip: Matlab executes FOR-loops slowly, so it is better to vectorize the operations: Make two matrices, where the first one contains beam 1..N-1, and the second contains beam 2..N, where N is the number of beams in the M-mode matrix. Complex conjugate the first matrix and multiply element by element with the other. Average along each column, and find the phase angle.

Part 6. Aliasing

Load the file `fastmotion.mat`. Make the image and estimate the rotation period T and time offset t_0 as for the first file. R and L are the same as in the first file. Use R, L, T og t_0 to plot the velocity as a function of time.

Estimate the phaseshift in the IQ-data for the whole sequence, and convert to velocity. Plot estimated velocity from the phase shift in the same plot as the calculated velocity. Comment on what happens where the velocity is large.

The phenomenon is called aliasing, and the limit for when this happenes is called the Nyquist limit. Derive the Nyquist limit for the velocity expressed with frequency f, speed of sound c and frame rate FR.

What is the Nyquist limit for the data in this exercise? How much should we increase the frame rate to be able to measure velocities of up to 20 cm/s using the same frequency? What if the frequency is reduced to 1.67 MHz?

Part 7. Angle between velocity and beam

Load the first beam (that is, the beam furthest to the left) from all the frames in the file `slowmotion.mat`. Estimate phaseshift and velocity.

Give an expression for the estimated velocity as a function of the real (absolute) velocity and the angle between the ultrasonic beam and direction of movement.

The movement of the phantom is vertical. The angle of the first beam in the sector is defined by the parameters`s.iq.StartAngleIQ_rad` (see Figure 1). The angle between the beams is given by `s.iq.AngleIncrementIQ_rad`. Calculate the velocity analytically and plot the result together with the estimated velocity in the same figure. What do you see?