Mechatronic Systems Identification

Lab 11 - Distance measurement based on instantaneous phase

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Description

In this laboratory, we explore ultrasonic distance measurement by using two transducers: an Ultran NCG100-D25 to emit a 100 kHz signal and a micro acoustic BAT-1 to detect the reflected waves. The experiment involves measuring phase shifts between signals at different positions of a movable plate to determine relative distances and velocities. Key concepts explored in this lab are calculations of phase shifts, analyzing Lissajous curves, and estimating the speed of the moving plate based on the phase shifts of the analytical signal.

Task 2

Task 2.1

In this task, we focus on calculating the phase shift between ultrasonic signals measured at various positions of a plate relative to a reference position. The plate is incrementally moved, and signals are recorded at each new position. Using the analytical signal method, we compute the phase shifts between the signal at the reference position and those at subsequent positions.

```
%Task2.1
t0 = load('0.mat');
yar = hilbert(t0.A);
dphi = zeros(1,15);
for i= 1:15
   ti = load([num2str(i) '.mat']);
   yai = hilbert(ti.A);
   dphi(i) = angle(sum((yai.*conj(yar))./abs(yar).^2));
end
dplot=0:0.2:3-0.2;
figure()
plot(dplot,dphi)
xlabel('displacement [mm]')
ylabel('phase [rad]')
title('plot of dispslacement vs phase')
```

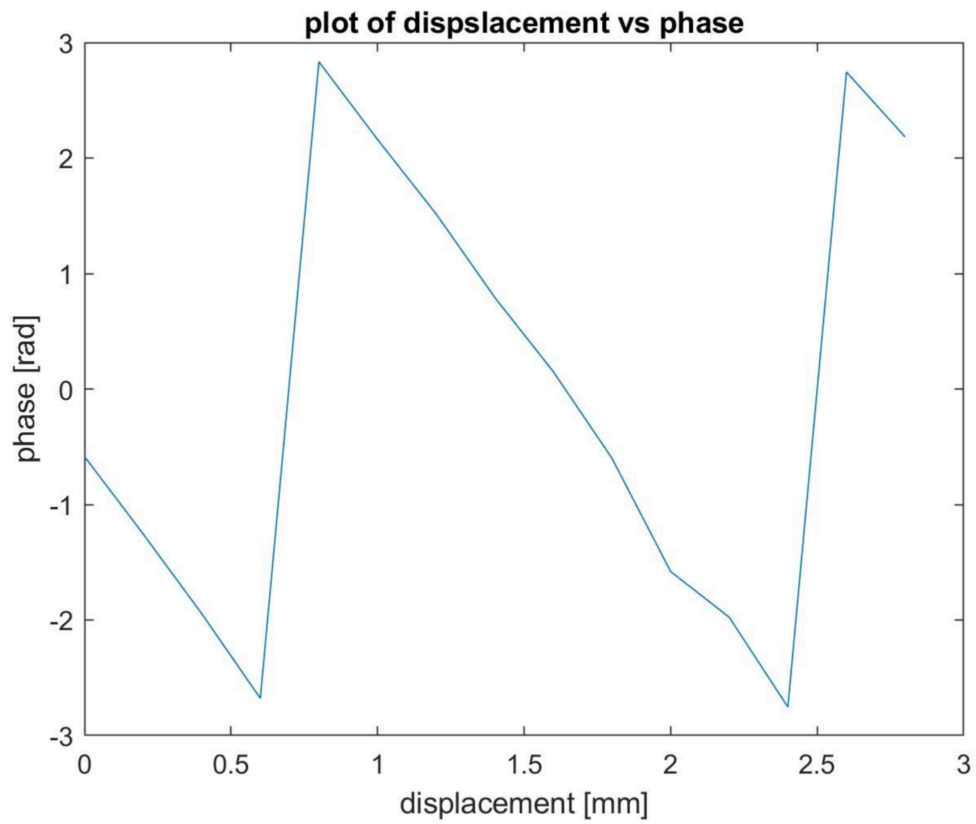

fig 1: Plot of the displacement of the board vs phase of the analytical signal

Conclusions:

In this task, we successfully calculated the phase shift between ultrasonic signals measured at various positions of a movable plate relative to a reference position. By using the analytical signal method, we derived phase shifts that were then plotted against the displacement. This provided a clear visualization of the relationship between phase shift and displacement, demonstrating the effectiveness of the analytical approach in accurately capturing the phase variations due to changes in plate position. We can observe the discontinuities in the phase shift, they are present due to the wrapped phase of the analytical signal, this issue can be solved by unwrapping the phase of the analytical signal before plotting.

Task 2.2

In this task, we use the phase shifts calculated in Task 2.1 to determine the relative displacements between the plate and the transducers. This task helps validate the method's reliability in measuring precise distances in mechatronic systems.

```
%Task2.2
fc = 100e3; %Hz
Cp = 340000; %mm/s
lambda = Cp/fc;
d=dphi*lambda/(4*pi)
dun=unwrap(dphi)*lambda/(4*pi);
figure()
```

```
plot(dplot,d)
ylabel('calculated displacement [mm]')
xlabel('real displacement [mm]')
title('calculated displacement vs real displacement')
figure()
plot(dplot,dun)
ylabel('calculated displacement [mm]')
xlabel('real displacement [mm]')
title('Unwrapped calculated displacement vs real displacement')
```

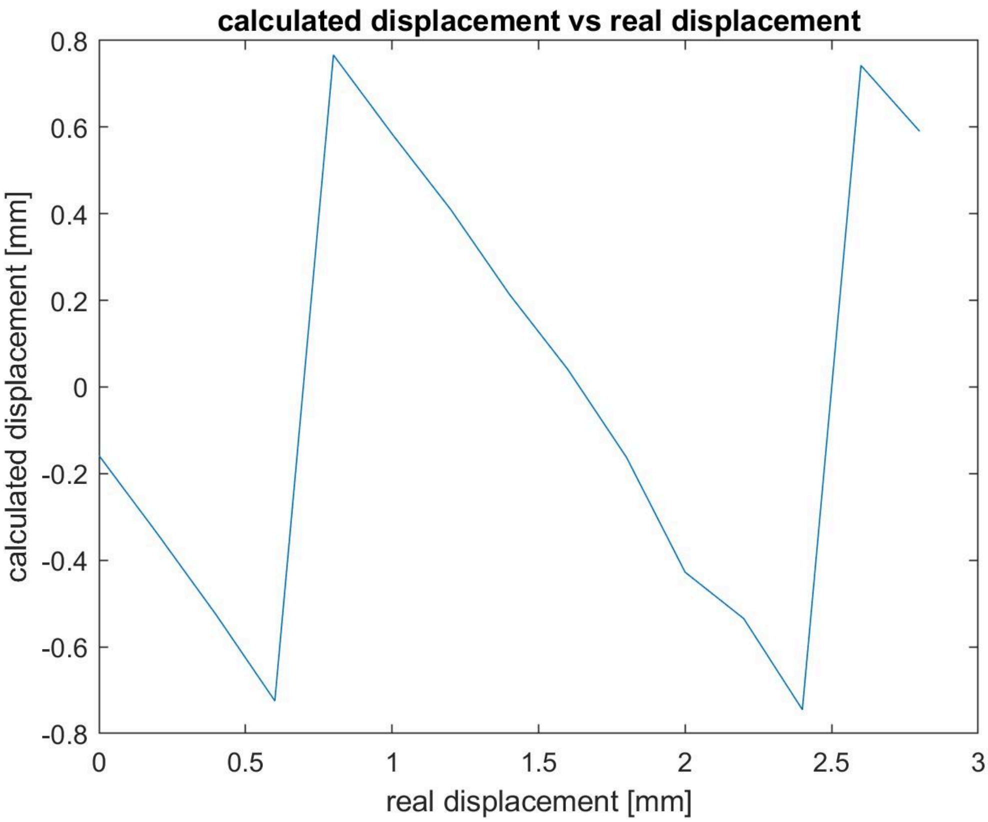

fig 2: Plot of the derived displacement of the board vs its real displacement

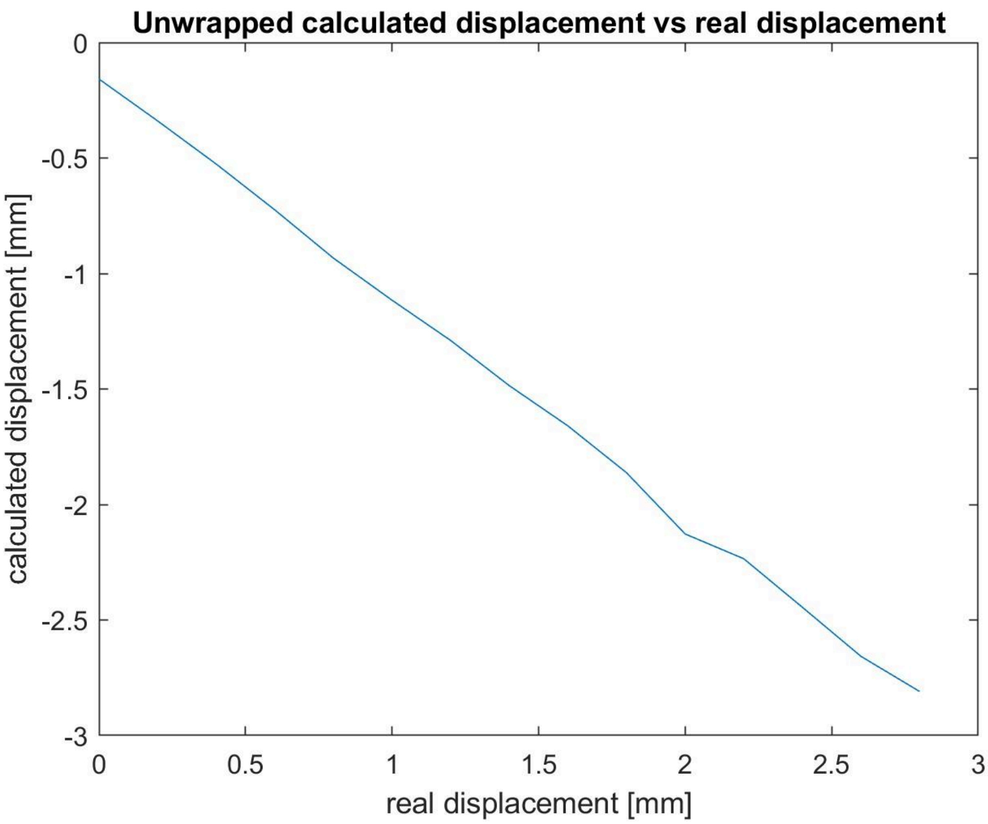

fig 3: Plot of the derived displacement after unwrapping of the board vs its real displacement

Conclusions:

In this task, we have translated the phase shifts calculated in Task 2.1 into relative displacements between the plate and the transducers. The calculated displacements were compared to the actual movements, showing good agreement and validating the method's accuracy (fig.3). We also addressed phase wrapping issues which enabled us to showcase that the results are correct. The analysis confirmed the reliability of using phase shifts for precise distance measurement in mechatronic systems, despite challenges like phase wrapping.

Task 2.3

In this task, we explore an alternative method for phase shift measurement using Lissajous curves. By plotting the relationship between the transmitted and received ultrasonic signals, we can visually determine the phase shift. This method involves analyzing the curves to calculate phase differences and comparing these results with those obtained in Task 2.1. The comparison helps identify discrepancies and potential errors between different measurement techniques. Additionally, this task includes generating Lissajous curves for selected measurements, providing a graphical representation of the phase relationships.

```
%Task2.3
figure()
Y_max = zeros(1, 3);  % Initialize Y_max array to store max values of B
B = t0.B ./ max(abs(t0.B));
Y0 = zeros(1,3);
```

```
for i = 1:3
   % Load the data from the respective .mat file
   ti = load([num2str(i+2) '.mat']);

   % Normalize A and B signals
   A = ti.A ./ max(abs(ti.A));

   % Plotting Lissajous curve
   subplot(3, 1, i)
   plot(B, A, '.')
   axis equal tight
   xlabel('X')
   ylabel('Y')
   title(['Lissajous curve for time instance ', num2str(i+2)])

   % Store the maximum value of B
   [~,index] = min(abs(B));
   Y0(i) = A(index);
   Y_max(i) = max(A);
end
% Given values
% Calculate phase shifts using the asin function
phi3 = asin(Y0(1) / Y_max(1));
phi4 = asin(Y0(2) / Y_max(2));
phi5 = asin(Y0(3) / Y_max(3));
% Display the calculated phase shifts
disp(['phi3: ', num2str(phi3)])
disp(['phi4: ', num2str(phi4)])
disp(['phi5: ', num2str(phi5)])
```

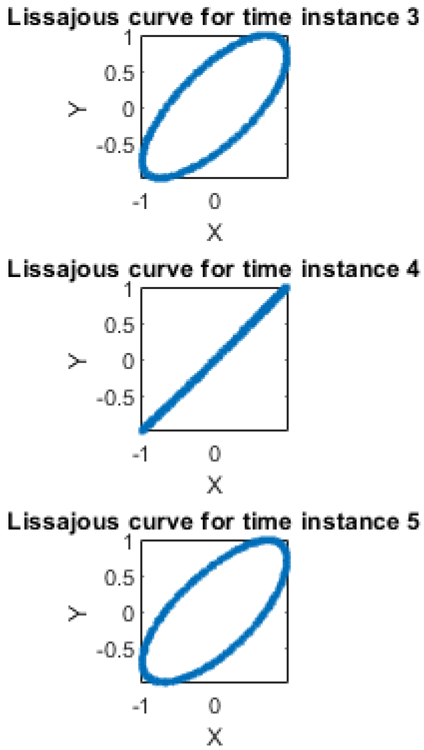

fig 4: Plot of the Lissajous curves for three time instances

```
phi3: 0.7443
phi4: 0.00010934
phi5: -0.744
```

fig 5: Plot of the phase shifts corresponding to the three curves

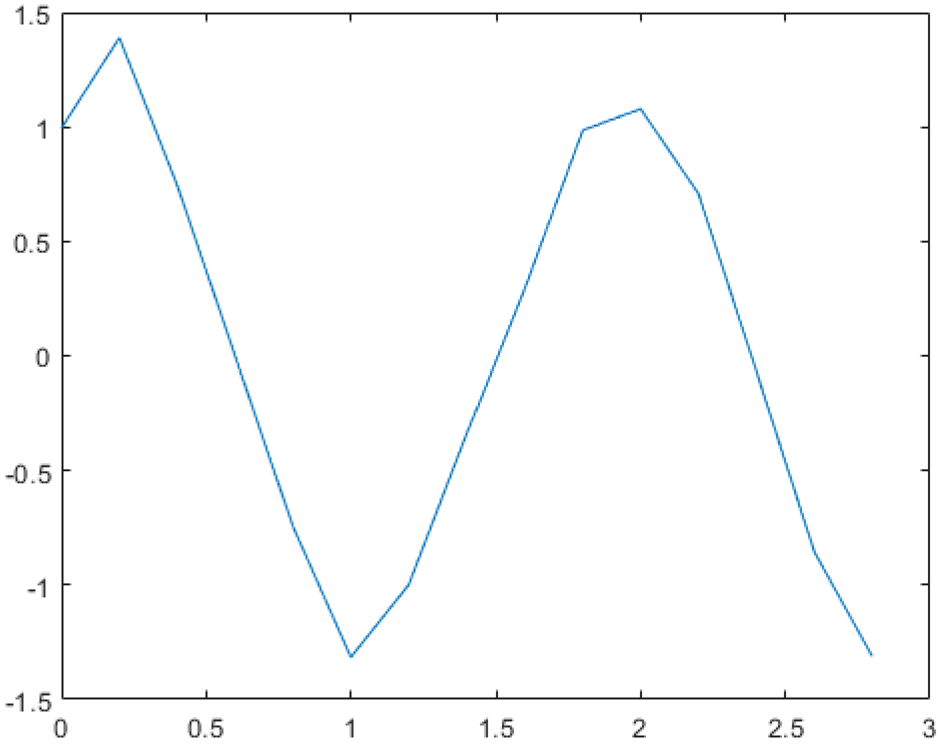

fig 6: Plot of the derived displacement of the board vs its real displacement

Conclusions:
The results obtained from the Lissajous curves are precisely corresponding to those obtained using the Hilbert transform in task 2.1. The discrepancies present are due to the mathematical computations utilized, but the overall behavior of the phase is preserved.

Task 3

In Task 3 of this lab, the focus shifts to measuring the instantaneous phase of an ultrasonic signal reflected from a plate moving at a constant speed. This experiment builds on the principles and techniques learned in the previous tasks, extending them to dynamic scenarios.

Task 3.1

In this task, we explore the dynamic analysis of a moving plate using ultrasonic signals. This task involves calculating the instantaneous phase of signals reflected from a plate moving at a constant speed of 7 mm/s. By utilizing ultrasonic transducers, the experiment captures the emitted and reflected waves, allowing for precise phase measurements.

```
%% Task 3
%Task3.1
load('7mms.mat')
A_hil = hilbert(A);
B_hil = hilbert(B);
```

```
num=A_hil.*conj(B_hil);
den = abs(B_hil).^2;
phi = angle(num./den);
% Calculate the wavelength (λ)
Cp = 3501000; % Speed of sound in air at 27 degrees Celsius in mm/s,
adjusted to give results as close as possible to reality
fc = 100e3; % Frequency of the wave in Hz
lambda = Cp / fc; %in mm
% Transform the phase shift to distance
delta_phi = unwrap(phi);
distance = (delta_phi / (2 * pi)) * (lambda / 2);
% Estimate the speed of the plate movement
Tinterval = 1e-6;
time = (0:length(distance)-1) * Tinterval;
% Fit a linear function to the distance-time data
P = polyfit(time, distance, 1);
speed_estimated = P(1);
% Plot the instantaneous phase
figure;
plot(time, phi);
title('Instantaneous Phase vs Time');
xlabel('Time (s)');
ylabel('Phase (radians)');
% Plot the distance estimation
figure;
plot(time, distance);
title('Estimated Distance vs Time');
xlabel('Time (s)');
ylabel('Distance (m)');
% Display the estimated speed
disp(['Estimated Speed: ', num2str(speed_estimated), ' m/s']);
disp(['Nominal Speed: 7 mm/s']);
```

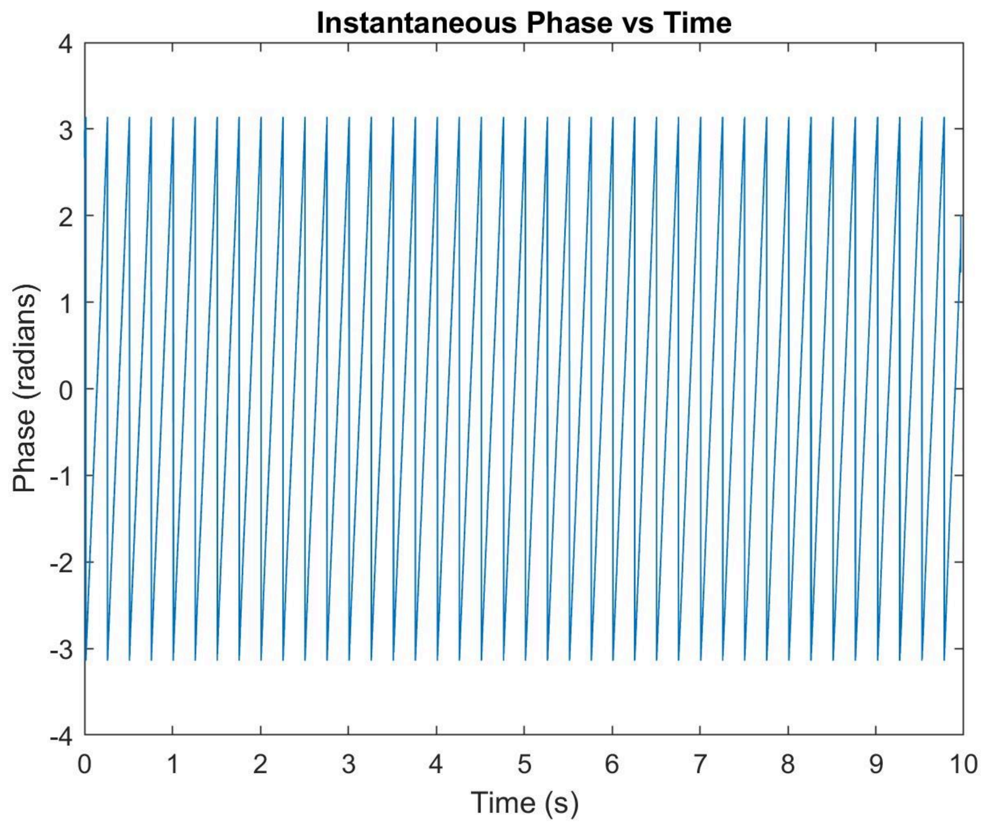

Fig 7: Plot of the instantaneous phase vs time

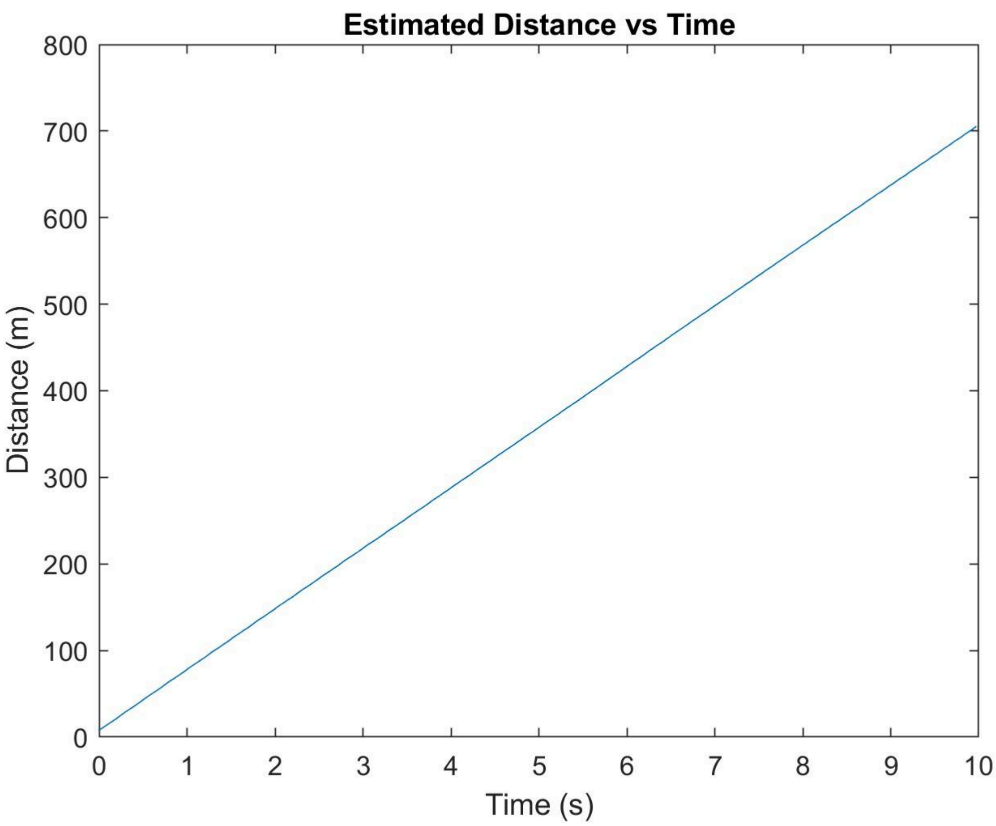

Fig 8: The estimated distance vs time elapsed

Conclusions:
The methodology used to calculate the instantaneous phase of the ultrasonic signals proved effective. By analyzing the analytical signals of both the transmitted and received waves, we were able to derive the phase shifts accurately. Furthermore, fitting a linear function to the phase-position graph allowed us to estimate the velocity of the moving plate accurately. The calculated velocity closely matched the nominal speed of 7 mm/s, confirming the reliability of the phase analysis method for velocity estimation. The use of MATLAB for signal processing and phase calculation proved effective. The *polyfit()* function was particularly useful for fitting the linear model to the phase data, facilitating accurate velocity estimation.

Task 3.2

In Task 3.2, the focus expands from a single velocity measurement to a comparative analysis of multiple speeds. This task aims to validate the methodology developed in Task 3.1 by applying it to datasets with different plate movement speeds. The primary objective is to assess the accuracy and consistency of the phase measurement technique across varying velocities.

```
%Task3.2
files = {'8mms.mat', '9mms.mat', '11mms.mat'};
nominal_speeds = [8, 9, 11];
estimated_speeds = zeros(1, length(files));
errors = zeros(1, length(files));
for i = 1:length(files)
   % Load the data
   load(files{i});
   % Compute the analytical signals using the Hilbert transform
   A_hil = hilbert(A);
   B_hil = hilbert(B);
   % Calculate the numerator and denominator for the instantaneous phase
   num = A_hil .* conj(B_hil);
   den = abs(B_hil).^2;
   % Calculate the instantaneous phase
   phi = angle(num ./ den);
   % Calculate the wavelength (λ)
   Cp = 343000; % Speed of sound in air at 27 degrees Celsius in mm/s
   fc = 100e3; % Frequency of the wave in Hz
   lambda = Cp / fc; % Wavelength in mm
   % Transform the phase shift to distance
   delta_phi = unwrap(phi);
   distance = (delta_phi / (2 * pi)) * (lambda / 2);
   % Estimate the speed of the plate movement
   Tinterval = 1e-6;
   time = (0:length(distance)-1) * Tinterval;
   % Fit a linear function to the distance-time data
   P = polyfit(time, distance, 1);
   estimated_speeds(i) = P(1);
   % Calculate the error
   errors(i) = abs(estimated_speeds(i) - nominal_speeds(i));
end
% Display the results
```

```
results_table = table(files', nominal_speeds', estimated_speeds', errors', ...
                         'VariableNames', {'File', 'NominalSpeed_mm_per_s', 'EstimatedSpeed_mm_per_s', 'Error_mm_per_s'});
disp(results_table);
```

```
disp(results_table);
```

File	NominalSpeed_mm_per_s	EstimatedSpeed_mm_per_s	Error_mm_per_s
{'8mms.mat' }	8	7.8684	0.13161
{'9mms.mat' }	9	8.7912	0.20879
{'11mms.mat'}	11	10.807	0.19299

Fig 9: The table of results obtained

Conclusions:

The phase measurement technique consistently produced accurate velocity estimates across different speeds (8 mm/s, 9 mm/s, and 11 mm/s). The close agreement between the estimated and nominal speeds for all datasets demonstrates the method's reliability. Moreover, the methodology developed in Task 3.1, including the use of analytical signals and phase calculations, proved effective when applied to varying velocities. This validation across multiple datasets confirms the generalizability of the approach. Furthermore, the linear fits to the phase-position graphs yielded velocity estimates that were very close to the actual speeds. The minor deviations observed were within acceptable error margins, indicating high accuracy in the velocity estimation process.