Subject: Noise Control Applications - Module 1 Assignement

Date: February 9, 2025 (Submitted)

Problem 1 - Cut-on Frequencies in Ducts and Pipes

The Matlab code for this problem is listed in Appendix 1.

Problem 1a

The lowest cut-on frequency for a rectangular duct with air flow is given by equation,

$$\mathrm{f_{cut-on}} = 0.5 \cdot \frac{\mathrm{c}}{\mathrm{L}} \tag{1}$$

where c is the speed of sound in air, 343 $\frac{\mathrm{m}}{\mathrm{s}}$, and L is the largest side of the rectangular cross-section.

With cross-sectional dimensions of $\mathrm{L_x}$ = 12 cm and $\mathrm{L_y}$ = 20 cm, the lowest cut-on frequency for this rectangular duct is,

$$\mathrm{f_{cut-on}} = 0.5 \cdot \frac{343\ \frac{\mathrm{m}}{\mathrm{s}}}{0.20\ \mathrm{m}} = \mathbf{857.5\ Hz}$$

Problem 1b

The lowest cut-on frequency for a circular duct with air flow with the same cross-sectional area as the rectangular duct in part (a.) can be calculated using equation,

$$\mathrm{f_{cut-on}} = 0.568 \cdot \frac{\mathrm{c}}{\mathrm{d}} \tag{2}$$

where c is the speed of sound in air, 343 $\frac{\mathrm{m}}{\mathrm{s}}$, and d is diameter of the circular duct.

The cross-sectional area of the rectangular duct is,

$$\mathrm{Area}_{\ \mathrm{rectangular\ duct}} = 0.12\ \mathrm{m}\ \cdot 0.20\ \mathrm{m} = 0.024\ \mathrm{m}$$

The corresponding diameter for this area is,

$$\mathrm{diameter} = \sqrt{\frac{0.24\ \mathrm{m}^2}{\pi}} \cdot 2 = 0.17\ \mathrm{m}$$

Using Eq. 2, the lowest cut-on frequency for this circular duct with air flow is,

$$\mathrm{f_{cut-on}} = 0.568 \cdot \frac{1,500\ \frac{\mathrm{m}}{\mathrm{s}}}{0.17\ \mathrm{m}} = \mathbf{1,114.5\ Hz}$$

Problem 1c

The lowest cut-on frequency for this circular duct with water flow can be calculated using Eq. 2,

$$f_{\text{cut-on}} = 0.568 \cdot \frac{1,500 \ \frac{\text{m}}{\text{s}}}{0.17 \ \text{m}} = \mathbf{4,873.9 \ Hz}$$

The lowest cut-on frequency for water is considerable larger than it is for air flow.

Problem 1d

The speed of sound in air is calculated by,

$$c = \sqrt{\gamma \cdot R \cdot T_K} \tag{3}$$

where $\gamma = 1.4$ is the ratio of specific heats, $R = 287 \ \frac{J}{kg \cdot K}$ is the gas constant, and T_K is the absolute temperature in Kelvin.

Figure 1 illustrates how the lowest cut-on frequency changes as the air heats from 0° to 500° Celsius.

The square-root relationship between temperature and the speed of sound in air is apparent and governs the behaviour of the cut-on frequency.

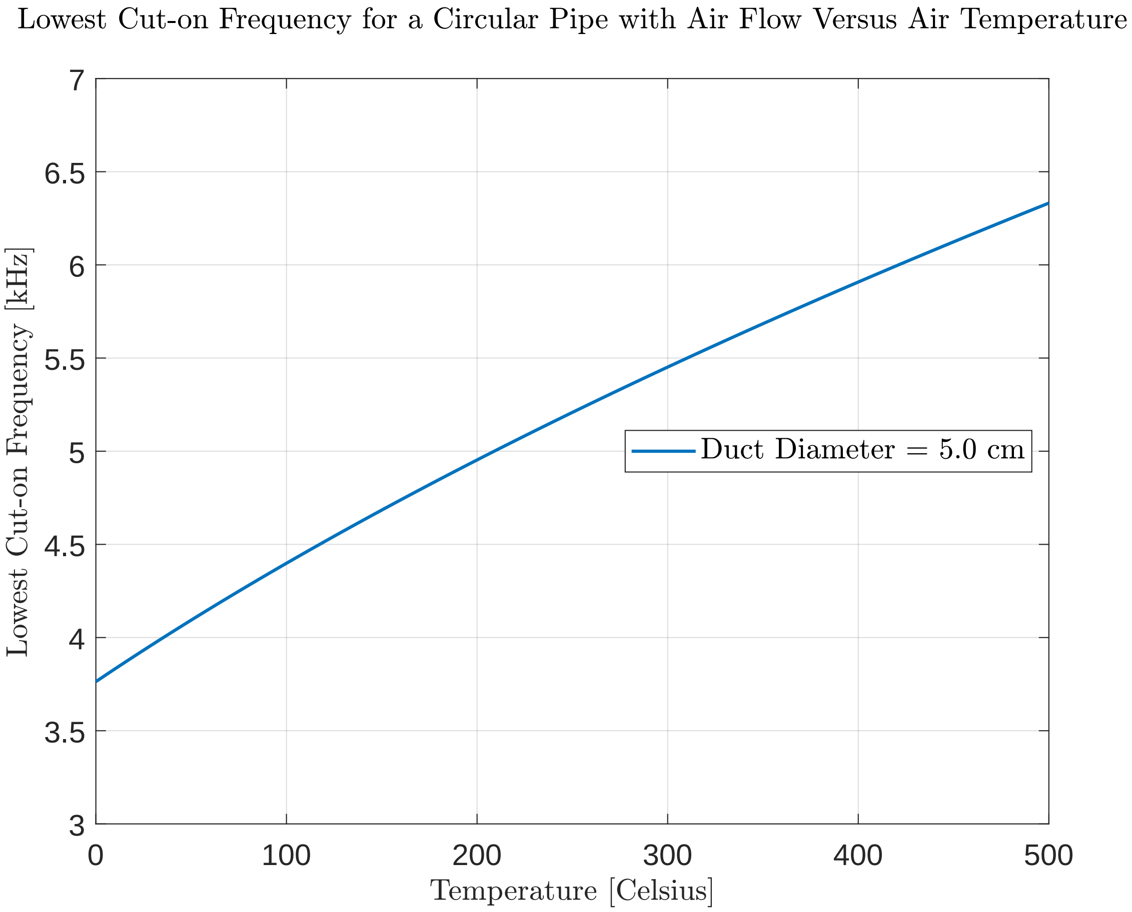

Figure 1: Lowest cut-on frequency for a circular 5 cm diameter duct versus air temperature.

Problem 1e

Question: Are cut-on frequencies higher for a circular or rectangular duct for a given cross-sectional area?

The lowest cut-on frequency is higher for a circular duct than for a rectangular duct for a given cross-sectional area.

For the dimensions given in class, the rectangular duct is not square. This produces a larger dimension and thus a smaller, lowest cut-on frequency. If the rectangular duct is square dimensions on the order of the circular duct diameter with the same cross-sectional area, the cut-on frequencies are approximately equal.

Question: What about in air versus water?

The lowest cut-on frequency is larger for water than for air. The cut-on frequency is proportional to the speed of sound and the speed of sound in water is greater than the speed of sound in air.

Question: What about cold versus hot air?

The lowest cut-on frequency is higher for warm air than it is for cold air.

Problem 2 - Muffler Design Comparison

The Matlab code for this problem is listed in Appendix 2.

For these muffler comparisons, the following assumptions were made:

- There is no flow.
- There are no resistive terms.
- The load impedance was not included because the transmission loss does not require them.
- For Parts b, c, and d, the side branch length offset, L_o, was set to zero.

Problems 2a, 2b, and 2c

Figure 2 shows the transmission loss profiles for a simple expansion chamber, a double-tuned expansion chamber, and a cascaded double-tuned expansion chamber muffler.

The peaks for the simple expansion chamber (red, dashed line) are approximately 22 dB and occur at frequencies with a wavelength that is a quarter of the length of the expansion chamber. Minimal loss occurs at half wavelength multiples.

The addition of the extension tube inside the muffler produces a quarter wavelength resonator. The side branch of Ji (2005; Slide 11, Lecture 3 notes) was used to calculate L_o. For the cascaded double-tuned expansion chamber, the extension tubes produce a secondary quarter wavelength resonator.

As noted in the office hours session, there is no damping which produces artificially high resonances.

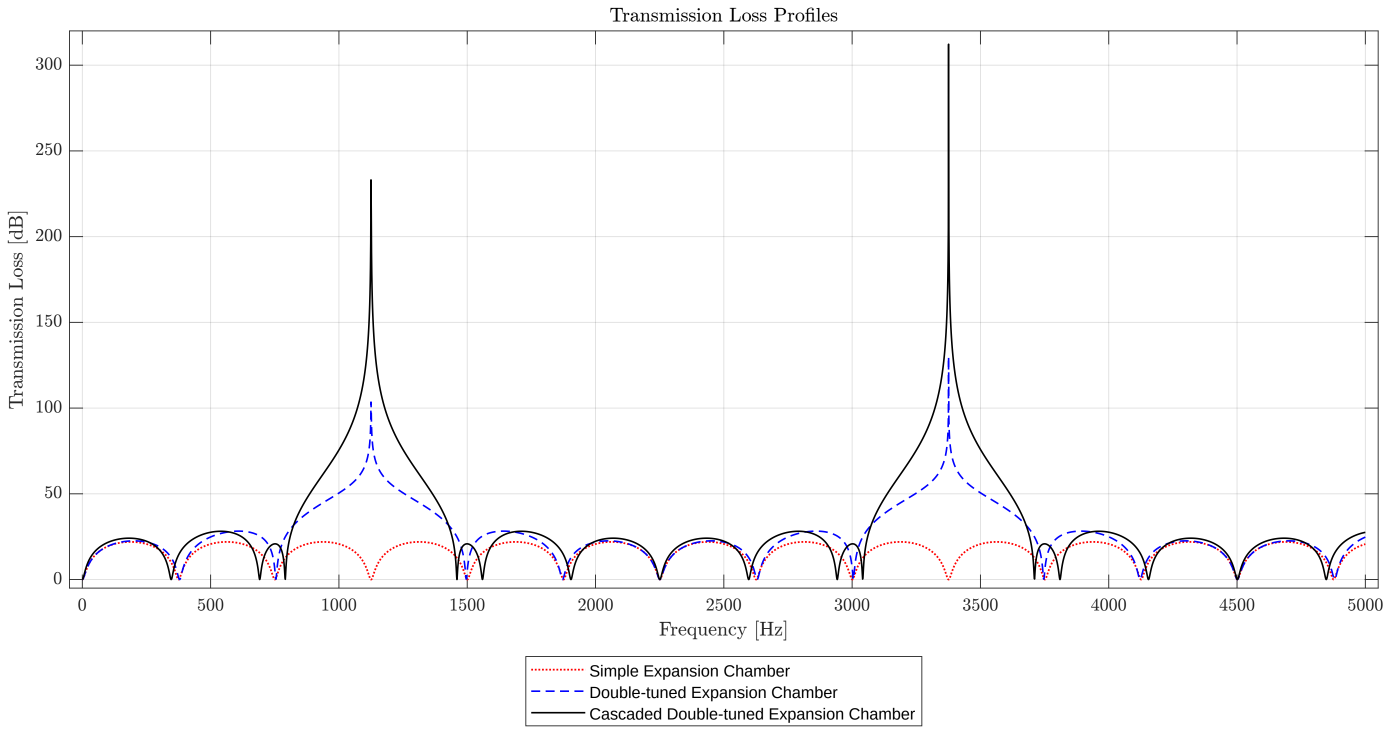

Figure 2: Transmission loss profiles for a simple expansion chamber, a double-tuned expansion chamber, and a cascaded double-tuned expansion chamber mufflers.

Problem 2d

Figure 3 shows the transmission loss profiles for a cascaded double-tuned expansion chamber, and a modified cascaded double-tuned expansion chamber muffler.

Two modifications were made to the original system:

1. The left 3" extension tube in the left chamber was shortened to 2" inches, making the respective muffler section 1" longer.
2. The left 3" extension tube in the right chamber was lengthened to 4", making the respective muffler section 1" shorter.

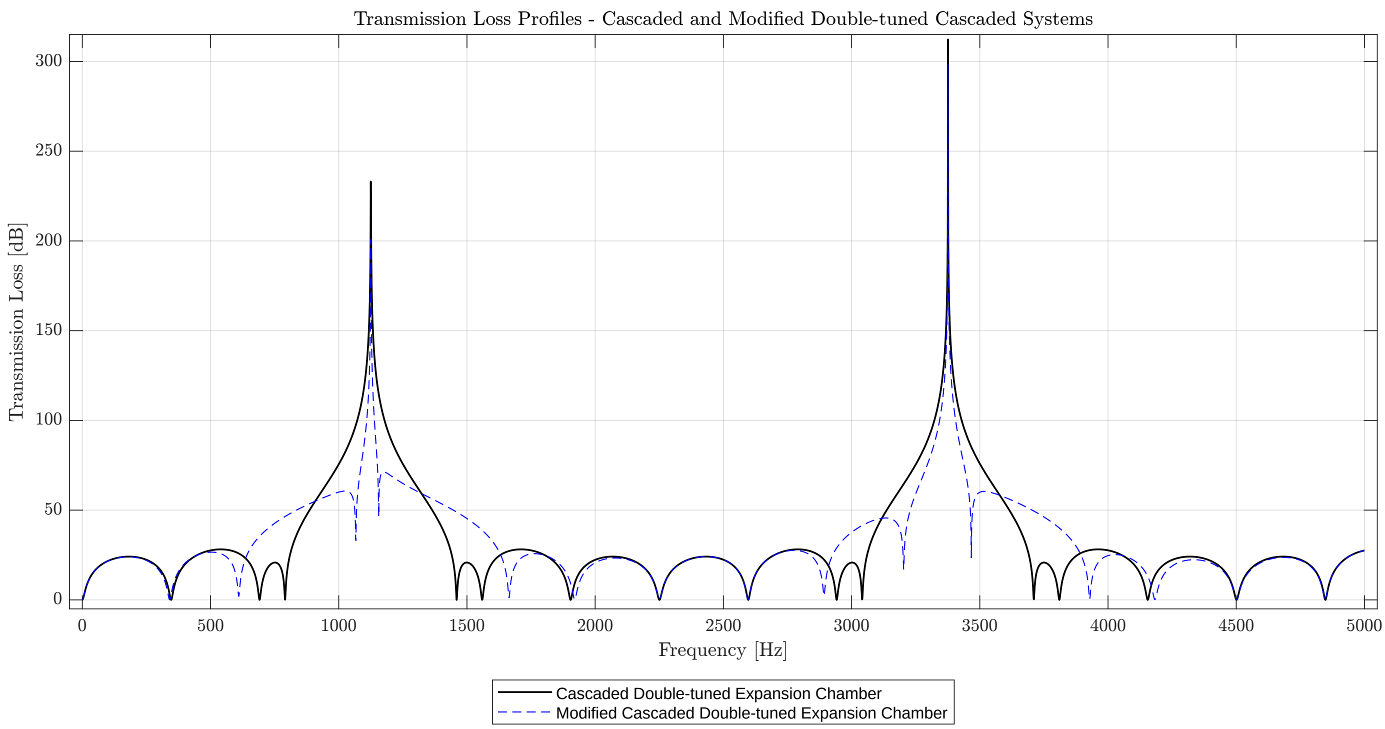

Figure 3: Transmission loss profiles for a cascaded double-tuned expansion chamber muffler and a modified version of this muffler.

These modifications change the symmetry of the cascaded system, and allow the resonate frequencies to be independently changed.

Problem 3 - Bugle Recorder

Problem 3a

The Matlab code for this problem is listed in Appendix 3.

Table 1 lists the length of the pipe section and the mouthpiece.

Item	Length [mm]
Pipe	145
Mouthpiece	90

Table 1: Calculated length of the pipe and length of the mouthpiece.

Problem 3b

Table 2 summarizes the placement of the holes for each note relative to the end of the pipe.

Note	Frequency [Hz]	Length from End of Pipe [mm]
C5	523	n/a
F5	698	87.75
A5	880	138.25
C6	1,046	0.168

Table 2: Hole placement distances.

Figure 4 shows the respective spectrum for each of the bugle recorder notes.

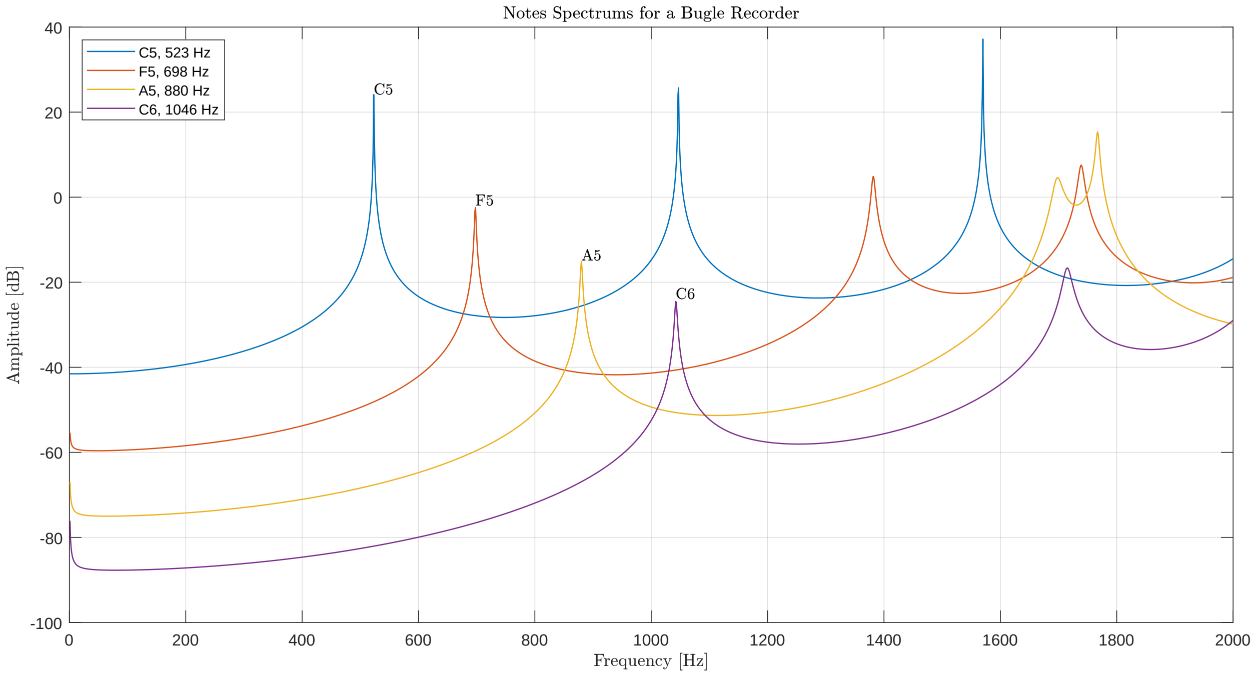

Figure 4: Spectrum for the C5, F5, A5, and C6 bugle recorder notes.

Problem 4 - Intake Duct

The Matlab code for this problem is listed in Appendix 4.

Problem 4a

Table 3 lists the Mach numbers for each pipe section. The flow rate is 0.017462 $\frac{m^3}{s}$.

Pipe	Area [m^2]	Mach Number [unitless]
Inlet	0.000507	-0.10047
Outlet	0.00811	-0.0062795

Table 3: Calculated Mach numbers.

Problems 4b, 4c, and 4d

Figure 5 shows the transmission loss profiles.

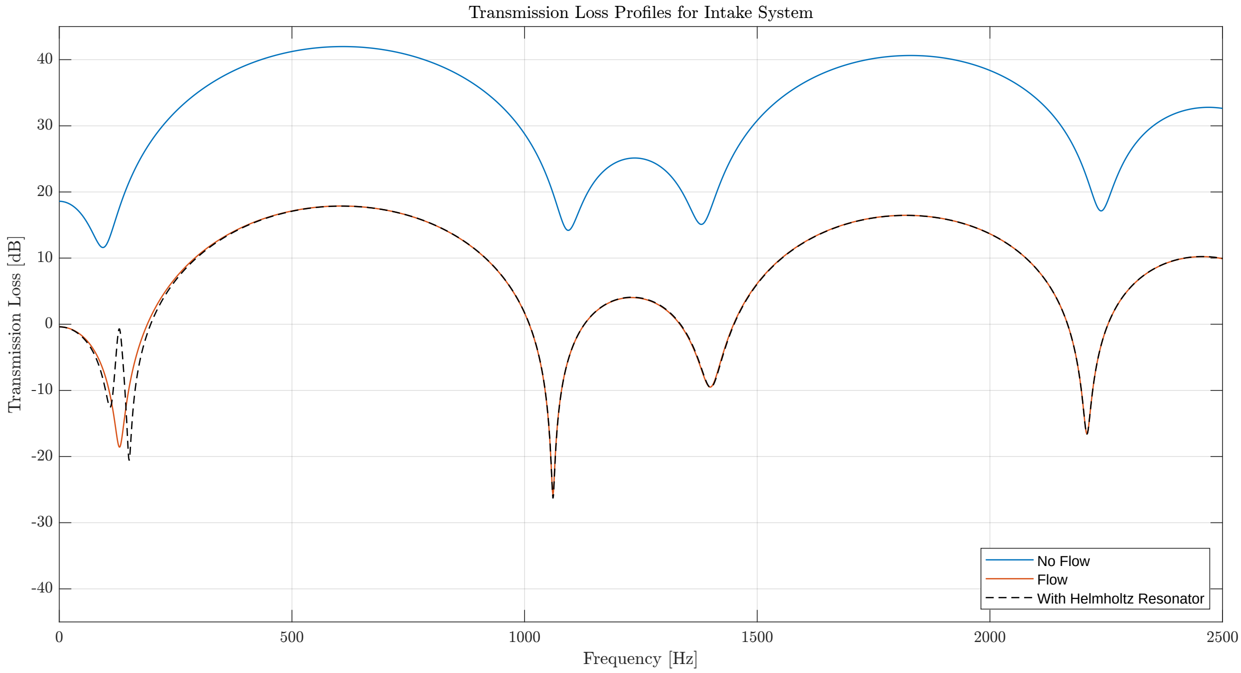

Figure 5: Transmission loss profiles for no flow, flow, and flow with a lossy Helmholtz resonator.

The addition of flow to the intake system introduces a slight phase delay, a lower overall level of loss (approximately 22 dB), and greater loss at the dips. The phase delay is easier to see at respective dips in the loss profile.

A phase delay is introduced by each of the pipe segments by the complex-exponential term in the transfer function. The attenuation is introduced by the expansion transfer function.

The target dip frequency is 129 Hz.

Table 4 lists the dimensions of the lossy Helmholtz resonator.

Item	**Measure]**
Cavity Diameter	0.254 m
Neck Diameter	0.0254 m
Neck Length	0.127 m
Neck Area	0.5e-3 m^2
Length Correction 1, L_{o1}	0.711 m
Length Correction 2, L_{o2}	0.3 m
Cavity Volume	8.0e-5 m^3
Q Factor	10

Table 4: Dimensions of the lossy Helmholtz resonator (see slide 15 of Lecture 3 notes).

The addition of the Helmholtz resonator offset the attenuation of the dip to approximately 0 dB.

Problem 5 - Intake Duct Silencer

The Matlab code for this problem is listed in Appendix 5.

My respective dip occurs at approximately 1,060 Hz, which has a loss of -25 dB. **For this problem I used the 940 Hz dip noted in the assignment discussion, requiring a 14 dB correction.**

Problem 5a

As noted in the discussion, there are two cases to be considered here.

First, with a liner thickness of 0.0381 meters and a half-liner width (circular duct) of 0.0113 meters, the expansion ratio, m, is 2.7. From Figure 8.37, a 14 dB overall loss has a total liner attenuation of 10 dB. The attenuation rate is about 78.4 $\frac{\mathrm{dB}}{\mathrm{m}}$.

Second,

Problem 5b

l, the liner thickness, is 0.0381 m. h, the liner half width, is 0.0113 m.

Problem 5c

The liner thickness ratio is 3.385 [unitless]. The normalized frequency is 0.0617 [unitless] for 940 Hz.

Problem 5d

With a liner thickness ratio of 3.385, the left-side, middle attenuation rate curve is applicable.

With $\frac{\mathrm{l}}{\mathrm{h}}$ of 4, curve 5 is used

Problem 5e

The flow resistivity, R_1, is about 1.74e5 $\frac{\mathrm{kg}}{\mathrm{m}^2\cdot\mathrm{s}}$ or rayl.

1 Appendix - Matlab Code for Problem 1

```matlab



%% Synopsis

% Question 1 - Cut-on Frequencies in Ducts and Pipes



%% Environment

close all; clear; clc;
% restoredefaultpath;

% addpath( genpath( '' ), '-begin' );
addpath( genpath( '../40 Assignments/00 Support' ), '-begin' );

% set( 0, 'DefaultFigurePosition', [ 400 400 900 400 ] ); % [ left bottom width height ]
set( 0, 'DefaultFigurePaperPositionMode', 'manual' );
set( 0, 'DefaultFigureWindowStyle', 'normal' );
set( 0, 'DefaultLineLineWidth', 1.5 );
set( 0, 'DefaultTextInterpreter', 'Latex' );

format ShortG;

pause( 1 );

PRINT_FIGURES = 0;



%% Define Constants and Anonymous Functions

c_air = 343; % The speed of sound in air (meters per second).
c_water = 1500; % The speed of sound in water (meters per second).

gamma = 1.4; % The ratio of specific heats [unitless].
R = 287; % The gas constant [Joules per ( kilogram * Kelvin)].


h_f_cut_on_rectangular_duct = @( c, L ) 0.5 .* c ./ L;
%
% c - The speed of sound.
% L - The largest cross-section dimension of the rectangular duct.


h_f_cut_on_circular_duct = @( c, d ) 0.568 .* c ./ d;
%
% c - The speec of sound.
% L - The diameter of the circular duct.


h_speed_of_sound_in_air = @( gamma, R, temperature_Kelvin ) sqrt( gamma .* R .*
    temperature_Kelvin );



%% Problem 1a

% The cross-sectional dimensions for the rectangular duct are: Lx = 12 cm and Ly = 20 cm.

% The largest dimension is Ly = 20 cm or 0.2 m.

% The cut-on frequency is,
h_f_cut_on_rectangular_duct( c_air, 0.2 ); % 857.5 Hz (shown in class 858 Hz)
    fprintf( 1, '\n Problem 1a: The lowest cut-on frequency for the rectangular pipe with air is
    %3.1f Hz.\n', h_f_cut_on_rectangular_duct( c_air, 0.2 ) );



%% Problem 1b

% The cross-sectional dimensions for the rectangular duct are: Lx = 12 cm and Ly = 20 cm.

% The cross-sectional area of the rectangular duct is 12 cm * 20 cm = 240 cm^2 or 0.024 m^2.
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```
rectangular_duct_cross_sectional_area = 0.12 * 0.20;  % 0.024 m^2

% The diameter of the circulat pipe is,
circular_duct_diameter = sqrt( 0.024 / pi ) * 2;  % 0.17481 meters
%
% Check:
    % pi * ( circular_duct_diameter / 2 )^2  CHECKED


% The cut-on frequency for the circular duct is,
h_f_cut_on_circular_duct( c_air, circular_duct_diameter );  % 1,114.5 Hz
    fprintf( 1, '\n Problem 1b:  The lowest cut-on frequency for the circular pipe (of equal area) with air is %3.1f Hz.\n', h_f_cut_on_circular_duct( c_air, circular_duct_diameter ) );



%% Problem 1c

% The cut-on frequency for the circular duct with water is,
h_f_cut_on_circular_duct( c_water, circular_duct_diameter );  % 4,873.9 Hz
    fprintf( 1, '\n Problem 1c:  The lowest cut-on frequency for the circular pipe (of equal area) with water is %3.1f Hz.\n', h_f_cut_on_circular_duct( c_water, circular_duct_diameter ) );

% The cut-on frequency should be higher because it is proportional to the
% speed of sound in a given medium.



%% Problem 1d

fprintf( 1, '\n Problem 1d:  See the figure.\n' );

temperature_range_celsius = 0:0.1:500;  % Celsius
    temperature_range_kelvin = temperature_range_celsius + 273.15;  % Kelvin


FONT_SIZE = 14;

figure( ); ...
    plot( temperature_range_celsius, h_f_cut_on_circular_duct( h_speed_of_sound_in_air( gamma, R, temperature_range_kelvin ), 0.05 ) ./ 1e3 );  grid on;
        legend( 'Duct Diameter = 5.0 cm', 'Location', 'East', 'FontSize', FONT_SIZE, 'Interpreter', 'Latex' );
        set( gca, 'FontSize', FONT_SIZE );
    %
    xlabel( 'Temperature [Celsius]', 'FontSize', FONT_SIZE );
        % xl = get( gca, 'xlabel' );    pxl = get( xl, 'position' );  pxl( 2 ) = 1.1 * pxl( 2 );
        %     set( xl, 'position', pxl );
    %
    ylabel( 'Lowest Cut-on Frequency [kHz]', 'FontSize', FONT_SIZE );
        % yl = get( gca, 'ylabel' );  pyl = get( yl, 'position' );  pyl( 1 ) = 1.2 * pyl( 1 );
        %     set( yl, 'position', pyl );
    %
    caption = sprintf( 'Lowest Cut-on Frequency for a Circular Pipe with Air Flow Versus Air Temperature\n' );
        title( caption, 'FontSize', FONT_SIZE );
    %
    ylim( [ 3  7 ] );



%% Problem 1e

fprintf( 1, '\n Problem 1e:  See Section Problem 1e of the Matlab script for the answers.\n\n' );


% Question:  Are cut-on frequencies higher for a circular or rectangular duct for a given cross-sectional area?

% The lowest cut-on frequency is higher for a circular duct than for a
% rectangular duct for a given cross-sectional area.

% For the dimensions given in class, the rectangular duct is not square.
% This produces a larger dimension and thus a smaller, lowest cut-on
% frequency.

% If the rectangular duct is square dimensions on the order of the circular
% duct diameter with the same cross-sectional area, the the cut-on
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% frequencies are approximately equal.


% Question:  What about in air versus water?

% The lowest cut-on frequency is larger with water than air.  This due to
% the fact that the cut-on frequency is proportional to the speed of sound
% and the speed of sound in water is greater than it is in air.


% Question:  What about cold versus hot air?

% For a circular pipe, the cut-on frequency is higher in warm air than cold
% air.



%% Clean-up

if ( ~isempty( findobj( 'Type', 'figure' ) ) )
    monitors = get( 0, 'MonitorPositions' );
        if ( size( monitors, 1 ) == 1 )
            autoArrangeFigures( 2, 2, 1 );
        elseif ( 1 < size( monitors, 1 ) )
            autoArrangeFigures( 2, 2, 1 );
        end
end

if ( PRINT_FIGURES == 1 )
    saveas( gcf, 'Cut-on Frequency Versus Temperature - Sunday, January 19, 2025.pdf' );
end

fprintf( 1, '\n\n\n*** Processing Complete ***\n\n\n' );
```

2 Appendix - Matlab Code for Problem 2

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%% Synopsis

% Question 2 — Muffler Design Comparison



%% Environment

close all; clear; clc;
% restoredefaultpath;

% addpath( genpath( '' ), '—begin' );
addpath( genpath( '../00 Support' ), '—begin' );

% set( 0, 'DefaultFigurePosition', [ 400 400 900 400 ] ); % [ left bottom width height ]
set( 0, 'DefaultFigurePaperPositionMode', 'manual' );
set( 0, 'DefaultFigureWindowStyle', 'normal' );
set( 0, 'DefaultLineLineWidth', 1.5 );
set( 0, 'DefaultTextInterpreter', 'Latex' );

format ShortG;

pause( 1 );

PRINT_FIGURES = 0;



%% Constants

rho0 = 1.21;  % Air density (kg per m^3).
c = 343;  % Speed of sound in air (meters per second).

frequency_set = 0:1:5e3;  % Hertz



%% Dimensions

convert.inches_to_meters = 0.0254;
convert.foot_to_meters = 0.3048;

dimensions.inlet_diameter_meters = 2 * convert.inches_to_meters;  % 0.0508 meters
dimensions.inlet_length_meters = 6 * convert.foot_to_meters;  % 1.82 meters

dimensions.muffler_diameter_meters = 10 * convert.inches_to_meters;  % 0.254 meters
dimensions.muffler_length_meters = 18 * convert.inches_to_meters;  % 0.4572 meters

dimensions.outlet_diameter_meters = 2 * convert.inches_to_meters;  % 0.0508 meters
dimensions.outlet_length_meters = 1 * convert.foot_to_meters;  % 0.3048 meters

outlet_flanged = false;

dimensions.overhang = 3 *convert.inches_to_meters;  % 0.0762 meters

segment_diameters = [ ...
    dimensions.outlet_diameter_meters, ...
    dimensions.muffler_diameter_meters, ...
    dimensions.inlet_diameter_meters, ...
    ].';
%
h_area_from_diameter = @( d ) pi .* d.^2 ./ 4;
%
segment_areas = h_area_from_diameter( segment_diameters );

segment_lengths = [ ...
    dimensions.outlet_length_meters, ...
    dimensions.muffler_length_meters, ...
    dimensions.inlet_length_meters, ...
    dimensions.overhang, ...
    ].';

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```matlab


%% Part a - Simple Expansion Chamber

nFreq = length( frequency_set );
    TL = zeros( nFreq, 1 );

for frequency_index = 1:1:nFreq

    f = frequency_set( frequency_index );

    T_total = [ 1 0; 0 1 ];

    T1 = duct_segment_transfer_matrix( f, rho0, c, 0.3048, 0.0020268 );  % Duct - Outlet
    T2 = duct_segment_transfer_matrix( f, rho0, c, 0.4572, 0.050671 );  % Duct
    T3 = duct_segment_transfer_matrix( f, rho0, c, 1.8288, 0.0020268 );  % Duct - Inlet

    T_net = T3 * T2 * T1 * T_total;
    % T_net = T_inlet *  T_total;  % Zero transmission loss for a straight duct.

    T11 = T_net(1, 1);  T12 = T_net(1, 2);  T21 = T_net(2, 1);  T22 = T_net(2, 2);
        TL( frequency_index ) = 10 * log10( abs( ( T11  +  0.0020268*T12/(rho0*c)  +  (rho0*c)*T21/0.0020268  +  T22 ) / 2 )^2 );
        %
        % The transmission loss calculation does not require a load impedance.

end

TL_parta = TL;  % The maximum peak value should be about 22 (21.952) dB.
%
% Expected behaviour:
%
%   1.)  0 dB at 0 Hz.
%   2.)  The transmission loss of a straight duct section is zero;  energy out equals energy in.

max( TL_parta );  % 22 dB



%% Part b - Double-tuned Expansion Chamber

annulus_area_squared_meters = pi/4 * ( 0.254^2 - 0.0508^2 );

L_o = 0;  % Assume that the Lo extension is neglible.


nFreq = length( frequency_set );
    TL = zeros( nFreq, 1 );

for frequency_index = 1:1:nFreq

    f = frequency_set( frequency_index );

    T_total = [ 1 0; 0 1 ];

    T1 = duct_segment_transfer_matrix( f, rho0, c, (0.3048 + 0.0762), 0.0020268 );
    T3 = duct_segment_transfer_matrix( f, rho0, c, (0.4572 - 2*0.0762), 0.050671 );
    T5 = duct_segment_transfer_matrix( f, rho0, c, (1.8288 + 0.0762), 0.0020268 );

    k = 2*pi*f/c;
        Z_A = -1j*rho0*c/annulus_area_squared_meters*cot(k * ( 0.0762 + L_o ) );
            T2 = [ 1  0;  1/Z_A  1 ];
                T4 = T2;

    T_net = T5 * T4 * T3 * T2 * T1 * T_total;


    T11 = T_net(1, 1);  T12 = T_net(1, 2);  T21 = T_net(2, 1);  T22 = T_net(2, 2);
        TL( frequency_index ) = 10 * log10( abs( ( T11  +  0.0020268*T12/(rho0*c)  +  (rho0*c)*T21/0.0020268  +  T22 ) / 2 )^2 );
        %
        % The transmission loss calculation does not require a load impedance.

end

TL_partb = TL;
%
% Expected behaviour:
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%
%   1.)  0 dB at 0 Hz.
%   2.)  0 dB at same locations as a simple expansion chamber.
%   3.)  Peaks at 1,125 Hz and 3,376 Hz;

% Frequency at which the quarter-wavelength is 0.0762 meters.
% 343 / ( 4 * 0.0762 );  % 1,125 Hz.

% Also work at three-quarter-wavelength.
% 3 * 1125;  % 3,375 Hz



%% Part c - Cascaded, Double-tuned Expansion Chamber

annulus_area_squared_meters = pi/4 * ( 0.254^2 - 0.0508^2 );

L_o = 0;  % Assume that the Lo extension is neglible.


nFreq = length( frequency_set );
    TL = zeros( nFreq, 1 );

for frequency_index = 1:1:nFreq

    f = frequency_set( frequency_index );
        k = 2*pi*f/c;
            Z_A = -1j*rho0*c/annulus_area_squared_meters*cot(k * ( 0.0762 + L_o ) );

    T_total = [ 1 0; 0 1 ];

    T1 = duct_segment_transfer_matrix( f, rho0, c, (0.3048 + 0.0762), 0.0020268 );  % Duct - Outlet
    T2 = [ 1  0;  1/Z_A  1 ];  % Straight Side Branch
    T3 = duct_segment_transfer_matrix( f, rho0, c, (0.2286 - 2*0.0762), 0.050671 );  % Duct
    T4 = T2;  % Straight Side Branch
    T5 = duct_segment_transfer_matrix( f, rho0, c, 2*0.0762, 0.050671 );  % Duct
    T6 = T2;  % Straight Side Branch
    T7 = T3;  % Duct
    T8 = T2;  % Straight Side Branch
    T9 = duct_segment_transfer_matrix( f, rho0, c, (1.8288 + 0.0762), 0.0020268 );  % Duct - Inlet

    T_net = T9 * T8 * T7 * T6 * T5 * T4 * T3 * T2 * T1 * T_total;

    T11 = T_net(1, 1);  T12 = T_net(1, 2);  T21 = T_net(2, 1);  T22 = T_net(2, 2);
        TL( frequency_index ) = 10 * log10( abs( ( T11  +  0.0020268*T12/(rho0*c)  +  (rho0*c)*T21/0.0020268  +  T22 ) / 2 )^2 );

end

TL_partc = TL;



%% Part d - Cascaded, Double-tuned Expansion Chamber

nFreq = length( frequency_set );
    TL = zeros( nFreq, 1 );

for frequency_index = 1:1:nFreq

    f = frequency_set( frequency_index );
        k = 2*pi*f/c;
            Z_A = -1j*rho0*c/annulus_area_squared_meters*cot(k * ( 0.0762 + L_o ) );

    T_total = [ 1 0; 0 1 ];

    T1 = duct_segment_transfer_matrix( f, rho0, c, (0.3048 + 0.0762), 0.0020268 );  % Duct - Outlet
    T2 = [ 1  0;  1/Z_A  1 ];  % Straight Side Branch
    T3 = duct_segment_transfer_matrix( f, rho0, c, 0.0076, 0.050671 );  % Duct
    T4 = T2;  % Straight Side Branch
    T5 = duct_segment_transfer_matrix( f, rho0, c, 2*0.0762, 0.050671 );  % Duct
    T6 = T2;  % Straight Side Branch
    T7 = duct_segment_transfer_matrix( f, rho0, c, (0.29718 - 2*0.0762), 0.050671 );  % Duct
    T8 = T2;  % Straight Side Branch
    T9 = duct_segment_transfer_matrix( f, rho0, c, (1.8288 + 0.0762), 0.0020268 );  % Duct -
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```
    Inlet

    T_net = T9 * T8 * T7 * T6 * T5 * T4 * T3 * T2 * T1 * T_total;

    T11 = T_net(1, 1);  T12 = T_net(1, 2);  T21 = T_net(2, 1);  T22 = T_net(2, 2);
        TL( frequency_index ) = 10 * log10( abs( ( T11 + 0.0020268*T12/(rho0*c) + (rho0*c)*T21/0.0020268 + T22 ) / 2 )^2 );

end

TL_partd = TL;



%% Plot Transmission Loss Profiles

Y_LIMITS = [ -5 320 ];

h_figure_1 = figure( ); ...
    plot( frequency_set, TL_parta, 'LineWidth', 1.0, 'LineStyle', ':', 'Color', 'r' );  hold on;
    plot( frequency_set, TL_partb, 'LineWidth', 0.9, 'LineStyle', '--', 'Color', 'b' );
    plot( frequency_set, TL_partc, 'LineWidth', 0.9, 'LineStyle', '-', 'Color', 'k' );  grid on;
        legend( ...
            'Simple Expansion Chamber', ...
            'Double-tuned Expansion Chamber', ...
            'Cascaded Double-tuned Expansion Chamber', ...
            'Location', 'SouthOutside' );
    xlabel( 'Frequency [Hz]' );  ylabel( 'Transmission Loss [dB]' );
    title( 'Transmission Loss Profiles' );
    %
    Ax = gca;
        Ax.XAxis.TickLabelInterpreter = 'latex';
        Ax.YAxis.TickLabelInterpreter = 'latex';
    %
    axis( [ -50 5e3+50 Y_LIMITS ] );


Y_LIMITS = [ -5 315 ];

h_figure_2 = figure( ); ...
    plot( frequency_set, TL_partc, 'LineWidth', 1.0, 'LineStyle', '-', 'Color', 'k' );  hold on;
    plot( frequency_set, TL_partd, 'LineWidth', 0.6, 'LineStyle', '--', 'Color', 'b' );  grid on;
        legend( ...
            'Cascaded Double-tuned Expansion Chamber', ...
            'Modified Cascaded Double-tuned Expansion Chamber', ...
            'Location', 'SouthOutside' );
    xlabel( 'Frequency [Hz]' );  ylabel( 'Transmission Loss [dB]' );
    title( 'Transmission Loss Profiles - Cascaded and Modified Double-tuned Cascaded Systems' );
    %
    Ax = gca;
        Ax.XAxis.TickLabelInterpreter = 'latex';
        Ax.YAxis.TickLabelInterpreter = 'latex';
    %
    axis( [ -50 5e3+50 Y_LIMITS ] );



%% Clean-up

if ( ~isempty( findobj( 'Type', 'figure' ) ) )
    monitors = get( 0, 'MonitorPositions' );
        if ( size( monitors, 1 ) == 1 )
            autoArrangeFigures( 2, 2, 1 );
        elseif ( 1 < size( monitors, 1 ) )
            autoArrangeFigures( 2, 2, 1 );
        end
end

if ( PRINT_FIGURES == 1 )
        exportgraphics( h_figure_1, 'Assignment 1 - Question 2 Figure All TL Profiles.pdf', 'Append', true );
        exportgraphics( h_figure_2, 'Assignment 1 - Question 2 Figure Comparison TL Plot For Cascaded Systems.pdf', 'Append', true );
end

fprintf( 1, '\n\n\n*** Processing Complete ***\n\n\n' );
```

3 Appendix - Matlab Code for Problem 3

```matlab



%% Synopsis

% Question 3 - Bugle Recorder



%% Environment

close all; clear; clc;
% restoredefaultpath;

% addpath( genpath( '' ), '-begin' );
addpath( genpath( '../00 Support' ), '-begin' );

% set( 0, 'DefaultFigurePosition', [ 400 400 900 400 ] ); % [ left bottom width height ]
set( 0, 'DefaultFigurePaperPositionMode', 'manual' );
set( 0, 'DefaultFigureWindowStyle', 'normal' );
set( 0, 'DefaultLineLineWidth', 0.8 );
set( 0, 'DefaultTextInterpreter', 'Latex' );

format ShortG;

pause( 1 );

PRINT_FIGURES = 0;



%% Constants and Anonymous Functions

rho0 = 1.21; % Density of air (kg per cubic-meter).
c = 343; % Speed of sound in air (meters per second).

h_RA_term_1 = @( rho0, c , S, k, delta_mu, D, w ) ( rho0*c/S ) * ( (k * sqrt( (2*3.178e-5) / (
    rho0*w) ) * D * 0.004 ) / (2*S) *1.4364 );
h_RA_term_2 = @( rho0, c , S, k, delta_mu, D, w, h ) ( rho0*c/S ) * 0.288*k*3.178e-5*log10((4*
    S)/(pi*h^2));
h_RA_term_3 = @( rho0, c , S, k, delta_mu, D, w, h ) ( rho0*c/S ) * (0.5*S*k^2)/(2*pi);
%
% See Equation 8.34 on page 479 of Bies et al (2024).



%% Part a

% The estimated total length of the recorder is 0.325 meters.

% Estimation of hole location was done by trial-and-error.

pipe_net_length = 0.325;
pipe_area = pi*0.009^2/4;

flanged = false;


frequency_set = 1:1:2e3;

nFreq = length( frequency_set );
    A = zeros( nFreq, 1 );

for frequency_index = 1:1:nFreq

    f = frequency_set( frequency_index );

    T_total = [ 1 0; 0 1 ];

    T_segment = duct_segment_transfer_matrix( f, rho0, c, pipe_net_length, pipe_area );

    T_total = T_segment * T_total;

    Z = open_end_impedance( f, rho0, c, 0, pipe_area, flanged );

```

```
    T11 = T_total(1, 1);  T12 = T_total(1, 2);
        A( frequency_index ) = -10*log10( abs( T11 + T12 / Z )^2 );

end

A_parta = A;  clear A;

% figure( ); ...
%     plot( frequency_set, A_parta, 'LineWidth', 0.8 );  grid on;
%     xlabel( 'Frequency [Hz]' );  ylabel( 'Amplitude [dB]' );
%         legend( 'C5' );

% return

%% Part b

epsilon = 0.006 / 0.004;  % Diameter of the hold divided by diameter of pipe section (1.5).

switch ( 3 )

    case 0  % Original Value

        L_o = 0.00001;  % Estimate
            L_e = 0.004 + 2*L_o;

        fprintf( 1, '\nZero - Percentage change in pipe thickness:  %3.1f%%.\n\n', ( L_e - 0.004 ) / 0.004 * 100 );

    case 1  % Ingard (2010)

        a = 0.006 / 2;

        L_o = ( 0.6*a + 0.85*a ) / 2;
            L_e = 0.004 + 2*L_o;

        fprintf( 1, '\nIngard (2010) - Percentage change in pipe thickness:  %3.1f%%.\n\n', ( L_e - 0.004 ) / 0.004 * 100 );

    case 2  % Kurze and Riedel (2013)

        e = epsilon^2;

        a = 0.006 / 2;

        L_o = pi*a*( 1 - 1.47*e^0.5 + 0.47*e^1.5 );
            L_e = 0.004 + 2*L_o;

        fprintf( 1, '\nKurze and Riedel (2013) - Percentage change in pipe thickness:  %3.1f%%.\n\n', ( L_e - 0.004 ) / 0.004 * 100 );

    case 3  % Ji (2005)

        a = 0.006 / 2;

        L_o = a*( 0.9326 - 0.6196*epsilon);
            L_e = 0.004 + 2*L_o;

        fprintf( 1, '\nJi (2005) - Percentage change in pipe thickness:  %3.1f%%.\n\n', ( L_e - 0.004 ) / 0.004 * 100 );

    otherwise
        error ( '*** Invalid SWITCH Index ***' );

end


duct_lengths = 0.235/4 * ones( 4, 1 );  % 523 Hz, all holes covered.


frequency_set = 0:1:2e3;

nFreq = length( frequency_set );
    A = zeros( nFreq, 1 );

for frequency_index = 1:1:nFreq

    f = frequency_set( frequency_index );

```

```
T_total = [ 1 0; 0 1 ];


Z_A = 1j * rho0 * (2 * pi * f) * L_e / ( pi*0.006^2/4 );
%
term_1 = h_RA_term_1( rho0, c, pi*(0.006)^2/4, 2*pi*f/c, sqrt( (2 * 3.178e-5 ) / ( 2*pi*f * rho0 ) ), pi * 0.006, 2*pi*f );
term_2 = h_RA_term_2( rho0, c, pi*(0.006)^2/4, 2*pi*f/c, sqrt( (2 * 3.178e-5 ) / ( 2*pi*f * rho0 ) ), pi * 0.006, 2*pi*f, 0.3 );
term_3 = h_RA_term_3( rho0, c, pi*(0.006)^2/4, 2*pi*f/c, sqrt( (2 * 3.178e-5 ) / ( 2*pi*f * rho0 ) ), pi * 0.006, 2*pi*f, 0.3 );
    R_A = term_1 + term_2 + term_3;
%
Z_A = Z_A + R_A;
    T_Hole = [ 1  0;  1/Z_A  1 ];


switch ( 0 )

    case 0  % All holes covered.  523 Hz
        T1 = duct_segment_transfer_matrix( f, rho0, c, 0.05875, pipe_area );  % Duct - Outlet
        T2 = [ 1 0;  0 1 ];  % Hole
        T3 = duct_segment_transfer_matrix( f, rho0, c, 0.05875, pipe_area );  % Duct
        T4 = [ 1 0;  0 1 ];  % Hole
        T5 = duct_segment_transfer_matrix( f, rho0, c, 0.05875, pipe_area );  % Duct
        T6 = [ 1 0;  0 1 ];  % Hole
        T7 = duct_segment_transfer_matrix( f, rho0, c, 0.05875, pipe_area );  % Duct

        % Check
        % 4 * 0.05875 = 0.235;

    case 1  % Hole 1 uncovered.  698 Hz
        T1 = duct_segment_transfer_matrix( f, rho0, c, 0.08775, pipe_area );  % Duct - Outlet
        T2 = T_Hole;
        T3 = duct_segment_transfer_matrix( f, rho0, c, 0.02975, pipe_area );  % Duct
        T4 = [ 1 0;  0 1 ];  % Hole
        T5 = duct_segment_transfer_matrix( f, rho0, c, 0.05875, pipe_area );  % Duct
        T6 = [ 1 0;  0 1 ];  % Hole
        T7 = duct_segment_transfer_matrix( f, rho0, c, 0.05875, pipe_area );  % Duct

        % Check
        % 0.08775 + 0.02975 + 2*0.05875 = 0.235;

    case 2  % Hole 2 uncovered.  880 Hz

        offset = 0.00625;  % 874

        T1 = duct_segment_transfer_matrix( f, rho0, c, 0.08775, pipe_area );  % Duct - Outlet
        T2 = T_Hole;
        T3 = duct_segment_transfer_matrix( f, rho0, c, 0.0505, pipe_area );  % Duct
        T4 = T_Hole;
        T5 = duct_segment_transfer_matrix( f, rho0, c, 0.038, pipe_area );  % Duct
        T6 = [ 1 0;  0 1 ];  % Hole
        T7 = duct_segment_transfer_matrix( f, rho0, c, 0.05875, pipe_area );  % Duct

        % Check
        % 0.08775 + 0.0505 + 0.038 + 0.05875 = 0.235

    case 3  % Hole 3 uncovered.  1,046 Hz

        T1 = duct_segment_transfer_matrix( f, rho0, c, 0.08775, pipe_area );  % Duct - Outlet
        T2 = T_Hole;
        T3 = duct_segment_transfer_matrix( f, rho0, c, 0.0505, pipe_area );  % Duct
        T4 = T_Hole;
        T5 = duct_segment_transfer_matrix( f, rho0, c, 0.02975, pipe_area );  % Duct
        T6 = T_Hole;
        T7 = duct_segment_transfer_matrix( f, rho0, c, 0.067, pipe_area );  % Duct

        % Check
        % 0.08775 + 0.0505 + 0.02975 + 0.067 = 0.235 m

end

    T8 = duct_segment_transfer_matrix( f, rho0, c, 0.09, pipe_area );  % Duct - Inlet

    T_total =  T8 * T7 * T6 * T5 * T4 * T3 * T2 * T1 * T_total;

    Z = open_end_impedance( f, rho0, c, 0, pipe_area, flanged );
```

```matlab

        T11 = T_total(1, 1);   T12 = T_total(1, 2);
            A( frequency_index ) = -10*log10( abs( T11 + T12 / Z )^2 );

end


% figure( ); ...
%     plot( frequency_set, A );   grid on;
%     xlabel( 'Frequency [Hz]' );   ylabel( 'Amplitude [dB]' );



%% Plot Note Set

load( 'A_C5_Data.mat' );   % Variable(s):   A_C5
load( 'A_F5_Data.mat' );   % Variable(s):   A_F5
load( 'A_A5_Data.mat' );   % Variable(s):   A_A5
load( 'A_C6_Data.mat' );   % Variable(s):   A_C6


h_figure_1 = figure( ); ...
    plot( frequency_set, A_C5 );   hold on;
        text( 523, 25, 'C5' );
    plot( frequency_set, A_F5 );
        text( 698, -1, 'F5' );
    plot( frequency_set, A_A5 );
        text( 880, -14, 'A5' );
    plot( frequency_set, A_C6 );   grid on;
        text( 1042, -23, 'C6' );
        %
        legend( 'C5, 523 Hz', 'F5, 698 Hz', 'A5, 880 Hz', 'C6, 1046 Hz', 'Location', 'NorthWest' );
    xlabel( 'Frequency [Hz]' );   ylabel( 'Amplitude [dB]' );
    title( 'Notes Spectrums for a Bugle Recorder' );



%% Clean-up

if ( ~isempty( findobj( 'Type', 'figure' ) ) )
    monitors = get( 0, 'MonitorPositions' );
        if ( size( monitors, 1 ) == 1 )
            autoArrangeFigures( 2, 2, 1 );
        elseif ( 1 < size( monitors, 1 ) )
            autoArrangeFigures( 2, 2, 1 );
        end
end

if ( PRINT_FIGURES == 1 )
        exportgraphics( h_figure_1, 'Assignment 1 - Question 3 Bugle Recorder Note Spectrums.pdf', 'Append', true );
end

fprintf( 1, '\n\n\n*** Processing Complete ***\n\n\n' );



%% Reference(s)
```

4 Appendix - Matlab Code for Problem 4

```
%% Synopsis

% Question 4 - Intake Duct



%% Environment

close all; clear; clc;
% restoredefaultpath;

% addpath( genpath( '' ), '-begin' );
addpath( genpath( '../40 Assignments/00 Support' ), '-begin' );

% set( 0, 'DefaultFigurePosition', [  400  400  900  400  ] ); % [ left bottom width height ]
set( 0, 'DefaultFigurePaperPositionMode', 'manual' );
set( 0, 'DefaultFigureWindowStyle', 'normal' );
set( 0, 'DefaultLineLineWidth', 0.8 );
set( 0, 'DefaultTextInterpreter', 'Latex' );

format ShortG;

pause( 1 );

PRINT_FIGURES = 0;



%% Constants

rho0 = 1.21;  % Density of air (kg per cubic-meter).
c = 343;  % Speed of sound in air (meters per second).

h_area = @( diameter )  pi * diameter^2 / 4;



%% Define Shape

% Source
duct_1.diameter_meters = 0.0254;  % meters
    duct_1.area = h_area( duct_1.diameter_meters );  % squared-meters
duct_1.length_meters = 0.1524;  % meters


% Outlet
duct_2.diameter_meters = 0.1016;  % 4 inches
    duct_2.area = h_area( duct_2.diameter_meters );
duct_2.length_meters = 0.127;  % 5 inches

% Flanged.

flow_rate_cubic_meters_per_second = 1.04772 / 60;  % or 37 cubic-feet per minute



%% Part a - Mach Numbers

% Calculate the Mach number of the flow in both pip sections.

duct_1.Mach = -1.0 * flow_rate_cubic_meters_per_second / ( (pi * duct_1.diameter_meters^2 / 4 ) * c );  % 0.100 unitless
duct_2.Mach = -1.0 * flow_rate_cubic_meters_per_second / ( (pi * duct_2.diameter_meters^2 / 4 ) * c );  % 0.00628 unitless



%% Part b - No Flow in Intake System

% The flange is not considered because transmission loss is calculated.
```

```
frequency_set = 0:1:2.5e3;
    nFreq = length( frequency_set );
        TL = zeros( nFreq, 1 );

for frequency_index = 1:1:nFreq

    f = frequency_set( frequency_index );

    T_total = [ 1 0; 0 1 ];

    T1 = duct_segment_transfer_matrix( f, rho0, c, duct_2.length_meters, duct_2.area );
    T2 = [ 1  0; 0  duct_2.area/duct_1.area ];
    T3 = duct_segment_transfer_matrix( f, rho0, c, duct_1.length_meters, duct_1.area );

    T_net = T3 * T2 * T1 * T_total;

    T11 = T_net(1, 1);  T12 = T_net(1, 2);  T21 = T_net(2, 1);  T22 = T_net(2, 2);
        TL( frequency_index ) = 10 * log10( abs( ( T11  +  duct_1.area*T12/(rho0*c)  +  (rho0*c)*
    T21/duct_2.area  +  T22 ) / 2 )^2 );

end


TL_part_b = TL;



%% Part c - Flow in Intake System

% The flange is not considered because transmission loss is calculated.


frequency_set = 0:1:2.5e3;
    nFreq = length( frequency_set );
        TL = zeros( nFreq, 1 );


for frequency_index = 1:1:nFreq

    f = frequency_set( frequency_index );

    T_total = [ 1 0; 0 1 ];

    T1 = duct_segment_transfer_matrix_flow( f, rho0, c, duct_2.length_meters, duct_2.area, duct_2
    .Mach );
    T2 = duct_expansion_connection_transfer_matrix( rho0, c, duct_2.area, duct_1.area, duct_1.
    Mach );
    T3 = duct_segment_transfer_matrix_flow( f, rho0, c, duct_1.length_meters, duct_1.area, duct_1
    .Mach );

    T_net = T3 * T2 * T1 * T_total;

    T11 = T_net(1, 1);  T12 = T_net(1, 2);  T21 = T_net(2, 1);  T22 = T_net(2, 2);
        TL( frequency_index ) = 10 * log10( abs( ( T11  +  duct_1.area*T12/(rho0*c)  +  (rho0*c)*
    T21/duct_2.area  +  T22 ) / 2 )^2 );

end


TL_part_c = TL;



%% Part d - Add a Lossy Helmholtz Resonator

% Use volume to tune resonator.


w_o = 2*pi*129;  % Target resonate frequency;  estimated from plot.

d_cavity = 10*0.0254;  % meters
d_neck = 0.0254;  % meters
L_neck = 5*0.0254;  % meters

S = d_neck^2*pi / 4;


Lo1 = 0.82 * ( 1 - 1.33*( d_neck / d_cavity ) );
```

```
Lo2 = 0.3;
    Le = L_neck + Lo1 + Lo2;

V = S / ( (w_o/c)^2 * Le );


R_A = rho0*c / 10 * sqrt( Le / ( S * V ) );

h_Z_A = @( f, Le, S, V, R_A )  1j*rho0*2*pi*f*Le/S  -  1j*rho0*c^2/(V*2*pi*f)  +  R_A;


frequency_set = 0:1:2.5e3;
    nFreq = length( frequency_set );
        TL = zeros( nFreq, 1 );

for frequency_index = 1:1:nFreq

    f = frequency_set( frequency_index );

    Z_A = h_Z_A( f, Le, S, V, R_A );

    T_total = [ 1 0; 0 1 ];

    T1 = duct_segment_transfer_matrix_flow( f, rho0, c, duct_2.length_meters, duct_2.area, duct_2
    .Mach );
    T2 = duct_expansion_connection_transfer_matrix( rho0, c, duct_2.area, duct_1.area, duct_1.
    Mach );
    T3 = [ 1   0;  1/Z_A   1 ];
    T4 = duct_segment_transfer_matrix_flow( f, rho0, c, duct_1.length_meters, duct_1.area, duct_1
    .Mach );

    T_net = T4 * T3 * T2 * T1 * T_total;

    T11 = T_net(1, 1);  T12 = T_net(1, 2);  T21 = T_net(2, 1);  T22 = T_net(2, 2);
        TL( frequency_index ) = 10 * log10( abs( ( T11  +  duct_1.area*T12/(rho0*c)  +  (rho0*c)*
    T21/duct_2.area  +  T22 ) / 2 )^2 );

end


TL_part_d = TL;



%% Plot

figure( ); ...
    plot( frequency_set, TL_part_b );  hold on;
    plot( frequency_set, TL_part_c );
    plot( frequency_set, TL_part_d, 'Color', 'k', 'LineStyle', '--' );  grid on;
        legend( 'No Flow', 'Flow', 'With Helmholtz Resonator', 'Location', 'SouthEast' );
    xlabel( 'Frequency [Hz]' );  ylabel( 'Transmission Loss [dB]' );
    title( 'Transmission Loss Profiles for Intake System' );
    ylim( [ -45 45 ] );
    %
    Ax = gca;
        Ax.XAxis.TickLabelInterpreter = 'latex';
        Ax.YAxis.TickLabelInterpreter = 'latex';



%% Clean-up

if ( ~isempty( findobj( 'Type', 'figure' ) ) )
    monitors = get( 0, 'MonitorPositions' );
        if ( size( monitors, 1 ) == 1 )
            autoArrangeFigures( 2, 2, 1 );
        elseif ( 1 < size( monitors, 1 ) )
            autoArrangeFigures( 2, 2, 1 );
        end
end

if ( PRINT_FIGURES == 1 )
        exportgraphics( gcf, 'Intake System.pdf', 'Append', true );
end

fprintf( 1, '\n\n\n*** Processing Complete ***\n\n\n' );
```

```
%% Reference(s)
```

5 Appendix - Matlab Code for Problem 5

```matlab

%% Synopsis

% Question 5 - Intake Duct Silencer



%% Environment

close all; clear; clc;
% restoredefaultpath;

% addpath( genpath( '' ), '-begin' );
addpath( genpath( '../40 Assignments/00 Support' ), '-begin' );

% set( 0, 'DefaultFigurePosition', [  400  400  900  400  ] ); % [ left bottom width height ]
set( 0, 'DefaultFigurePaperPositionMode', 'manual' );
set( 0, 'DefaultFigureWindowStyle', 'normal' );
set( 0, 'DefaultLineLineWidth', 1.5 );
set( 0, 'DefaultTextInterpreter', 'Latex' );

format ShortG;

pause( 1 );



%% Part a

% The considered dip frequency 940 Hz.

% The additional attentuatio required is 14 dB.

liner_thickness = 0.0381;  % meters
    h = sqrt( ( pi*( 0.1016 - 2*liner_thickness  )^2 ) / 4 );  % 0.0113 meters

m = 1 + liner_thickness/h;  % 2.7

% As noted in the discussion, there are two cases to be considered here.
%
% Figure 8.37 considers the combined effect of the expansion and the liner.
% In Problem 4, the effect of the expansion was calculated, so including it
% here would include its effect twice.  Therefore, with an m of 1, there is
% not additional attenuation with the linear.
%
% The second case is to consider the m value of 2.7, which provides
% additional attenuation.  From Figure 8.37, the total attenuation of
% the lining is 10 dB.
attenuation_rate = 10 / 0.127;  % 78.4  dB per meter



%% Part b

% For a circular duct.

liner_thickness = 0.0381;  % meters
half_diameter_of_open_orifice = 0.0127;  % meters

h = sqrt(pi) * half_diameter_of_open_orifice / 2;  % 0.0113 meters



%% Part c

% The liner thickness ratio is,
liner_thickness / h;  % 3.3852 unitless

% The normalized frequency is,
( 2 * h ) / ( 343 / 940 );  % 0.06169 unitless



%% Part d
```

```matlab

% The approximate resistivity parameter is 4.



%% Part e

% Calculate the flow resistivity.

rho0 = 1.21;  % Density of air (kg per cubic-meter).
c = 343;  % Speed of sound in air (meters per second).

R1 = 16 * rho0*c / liner_thickness;  % 1.74e5 kg / m^3*s


%% Clean-up

if ( ~isempty( findobj( 'Type', 'figure' ) ) )
    monitors = get( 0, 'MonitorPositions' );
        if ( size( monitors, 1 ) == 1 )
            autoArrangeFigures( 2, 2, 1 );
        elseif ( 1 < size( monitors, 1 ) )
            autoArrangeFigures( 2, 2, 1 );
        end
end


fprintf( 1, '\n\n\n*** Processing Complete ***\n\n\n' );



%% Reference(s)
```