Oscillometric model

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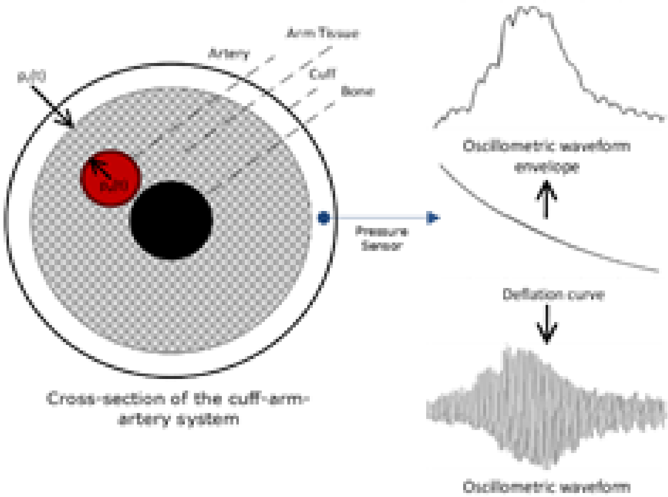
This code was developed by Miodrag Bolic for the book PERVASIVE CARDIAC AND RESPIRATORY MONITORING DEVICES: https://github.com/Health-Devices/CARDIAC-RESPIRATORY-MONITORING

```
% Changing the path from main_folder to a particular chapter
main_path=fileparts(which('Main_Content.mlx'));
if ~isempty(main_path)
    %addpath(append(main_path,'/Chapter2'))
    cd (append(main_path,'/Chapter5/Oscilometric_Circuit'))
    addpath(append(main_path,'/Service'))
end
SAVE_FLAG=0; % saving the figures in a file
```

Introduction

This notebook provides introduction to the circuit for obtaining pressure signal and algorithms for blood pressure measurements.

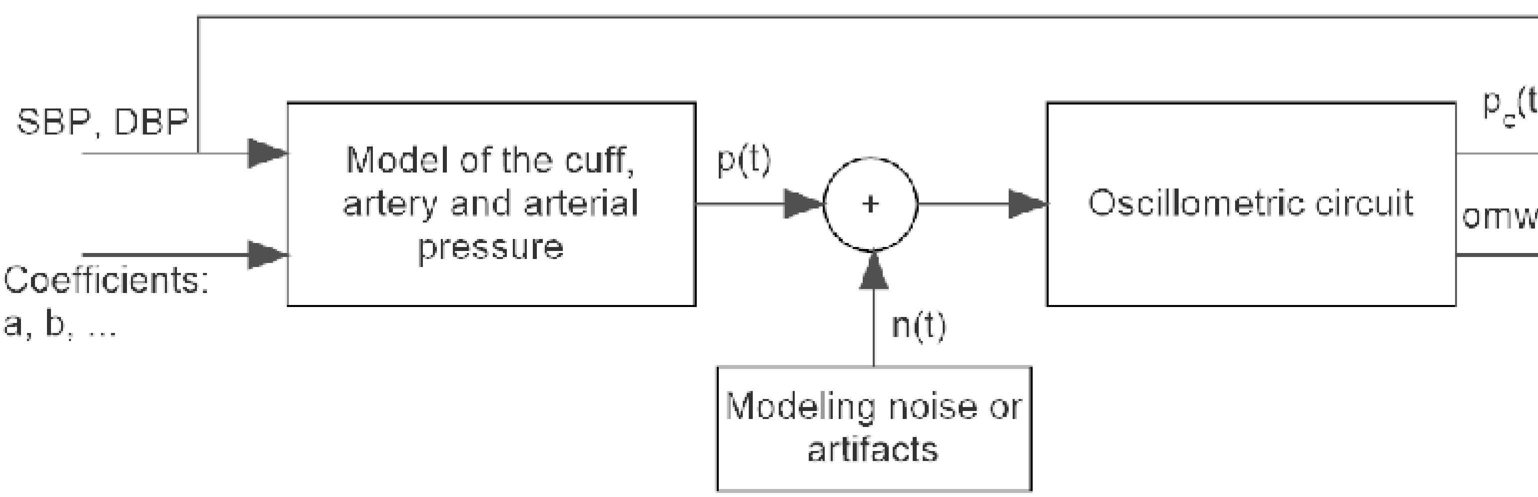
Figure below represents the cross-section of the cuff, arm and artery system. The grey circle is the cross-section of the upper arm with the bone and the artery shown inside. The outermost black circle represents the cuff that is wrapped around the arm. Cuff pressure is denoted as $p_c(t)$. The internal pressure in the artery is denoted as $p_a(t)$. The signal at the output of the pressure transducer represent the pressure obtained during cuff deflation (deflation curve). Small pulses are supperimposed on the deflation curve and these pulses are extracted and amplified in the bottom right corner of Figure. They form a waveform called the oscillometric waveform. The envelope of the oscillometric waveform is called oscillometric waveform envelope. Systolic blood pressure (SBP) and diastolic blood pressure (DBP) are obtained by processing the oscillometric envelope using oscillometric algorithms.



The model includes:

1. Model of the cuff and the artery that is used to generate the oscillometric waveform
2. Oscillometric circuit
3. Oscillometric algorithms
4. Analysis of the accuracy of the oscillometric algorithm

The elements of the model are connected as in the figure bellow. The output of the cuff/artery/arm model is the composite pressure P(t) that includes the cuff pressure with superimposed arterial pulses. We can add Gaussian noise, 60 Hz interference signal and/or motion artifacts to it. This signal is connected to the pressure sensor where it is filtered and amplified to extract the cuff pressure $p_c(t)$ and the oscillometric signal omw(t). These two signals are used as an input to the escillometric algorithm that produces the estimated of systolic and diastolic blood pressure. The mean square error is calculated in the end.



Arm-Artery System Model

The arm-artery model is based on the paper:

[1] C. F. Babbs, "Oscillometric measurement of systolic and diastolic blood pressures validated in a physiologic mathematical model," BioMedical Engineering OnLine, Vol. 11, no: 56, 2012.

The model introduces transmural pressure $P_t(t) = P_a(t) – P_c(t)$ that represents the pressure of both sides of the arterial wall. When the cuff is placed around the upper arm and the pressure is applied, the volume of the artery reduces. The volume of the artery is related to the pressure as

$$V_a(t) = \left\{ \begin{array}{c} V_{a0} e^{ap_t(t)},\ for\ P_t(t) < 0 \\ V_{a0}\left[1 + \frac{a}{b}\left(1 - e^{-bP_t(t)}\right)\right],\ for\ P_t(t) \geq 0 \end{array} \right) \quad (1)$$

During cuff deflation, total pressure is computed as the sum of the decreasing cuff pressure with the rate r, and superimposed variations due to arterial volume Va(t) changes in each cardiac cycle:

$$P(t) = P_0 - rt + P_{ath} + V_a(t)/C_{cuff}(t) \quad (2)$$

$C_{cuff}(t)$ is the compliance of the cuff and it can be modeled as $C_{cuff}\ (t) = V_0/(P_0 - rt + P_{ath})$, where P_{ath} is the athnospheric pressure and V_0 is the maximum volume of hte cuff.

Next, we will introduce the parameters of the model including:

Pressure parameters and signals (with the time index t):

- systolic pressure: SBP
- diastolic pressure: DBP
- pulse pressure: PP= SBP-DBP
- arterial pressure: Pa(t)
- transmural pressure: Pt(t) where $Pt = Pa - (P0 - rate \cdot t)$;

Deflation and cuff parameters

- pressure up the which the duff is inflated: P0=SBP+30
- rate of cuff deflation: rate (r)
- volume of the cuff: V0

Artery parameters

- radius of the artery in cm: r
- length of the artery covered by the cuff in cm: L
- resting artery volume: $Va0 = 3.14 \cdot r^2 \cdot L$
- the volume of the artery $V_a(t)$ vs transmural pressure as in (1)
- compliance constants of the arterial model: a and b

- heart rate in Hz: heart_rate

Matlab model of the Arm-Artery System

Several parameters that are not related to the model will be introduced first:

```
clear all
delta_T=0.005;
fs=1/delta_T;
plotting=1;
```

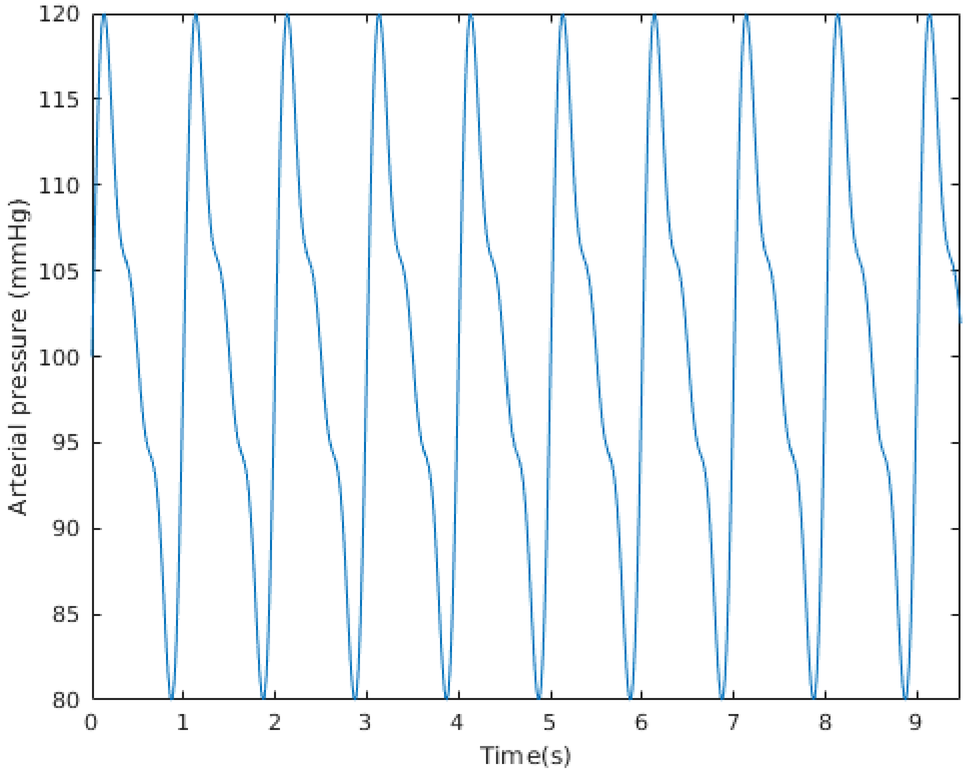
We will first simulate the signal for normal values of blood rpessure of SBP=120 mmHg and DBP=80 mmHg.

```


SBP=120;
DBP=80;
%Computing the parameters
PP= SBP-DBP; % pulse pressure
P0=SBP+30; % start of cuff deflation
heart_rate=1; % in Hz
```

Arterial pulse Pa(t) is modeled as Fourier series based on [1]. We also compute its derivative dP_dt. Please note that the shape does not eactly follows the arterial pulse pressure morphology.

```
% Model of the arterial pulse and its derivative
delta_T=1/fs;
t=0:delta_T:55;
omega=2*pi*heart_rate;
Pa=DBP+0.5*PP+0.36*PP*(sin(omega*t)+0.5*sin(2*omega*t)+0.25*sin(3*omega*t));
dP_dt=0.36*PP*omega*(cos(omega*t)+cos(2*omega*t)+0.75*cos(3*omega*t));
if plotting ==1
    figure; plot(t,Pa)
    xlabel("Time(s)")
    ylabel("Arterial pressure (mmHg)")
    xlim([0.00 9.47])
    ylim([80 120.0])
end
```

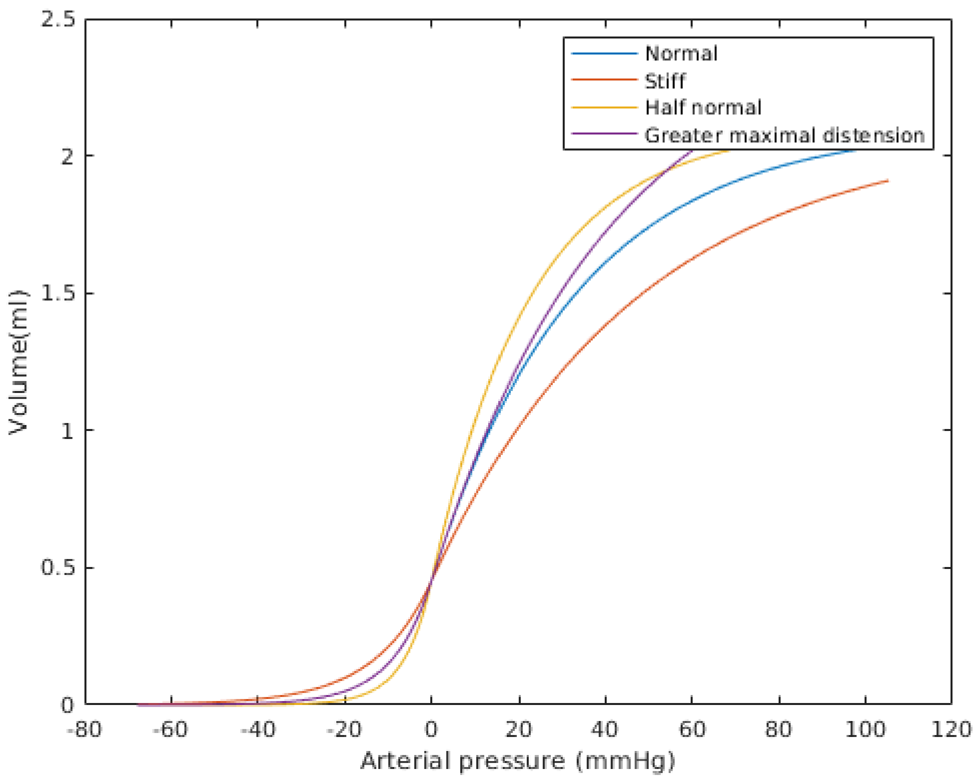


Next, we will show **arterial volume** against the transmural pressure for several different patient conditions.

Compliance constants a and b allow us to simulate different patient conditions. Increasing a and b in proportion results in larger volume changes for a given pressure change and therefore larger values of a and b can be used to represent a more compliant artery. Decreasing a and b in proportion reduces the volume change for a given pressure change and so that smaller values of a and b represent a stiffer artery. Increasing the ratio a/b represents a greater maximal distension. Decreasing the ratio a/b represents a smaller maximal distension. We will analyze the shape of the Va(t) vs Pt(t) curve for the cases of: normal arterial stifness, stiff artery, artery with hhalf normal stifness and the artery with increased maximal distension. Please note that the blood pressure should normally increase when the artery is stiffer - however in this example we will keep SBP and DBP the same and only chage complieance parameters a and b.

```
ArteryProp.a(1)=0.11; ArteryProp.b(1)=0.03; ArteryProp.c(1)="Normal";
ArteryProp.a(2)=0.076; ArteryProp.b(2)=0.021; ArteryProp.c(2)="Stiff";
ArteryProp.a(3)=0.158; ArteryProp.b(3)=0.0432; ArteryProp.c(3)="Half normal";
ArteryProp.a(4)=0.11; ArteryProp.b(4)=0.0244; ArteryProp.c(4)="Greater maximal distensi
r=0.12;     % radius of the artery in cm
L=10;       % length of the artery covered by the cuff in cm
Va0=3.14*(r)^2*L; %The resting artery volume
rate=2.5;   % Deflation rate in mmHg/s
legend_arter=[];
% Volume vs transmural pressure - equation (4) from the paper [1]
for j=1:length(ArteryProp.a)
    a=ArteryProp.a(j);
    b=ArteryProp.b(j);
    for i=1:length(t)
```

```
        Pt(i)=Pa(i)-P0+rate*t(i);
        if Pt(i)<0
            Va(i,j)=Va0*exp(a*Pt(i));
        else
            Va(i,j)=Va0*(1+(1-exp(-b*Pt(i)))*a/b);
        end
    end
    if plotting ==1
        plot(Pt,Va(:,j))
        legend_arter=[legend_arter ArteryProp.c(j)];
        hold on
    end
end
legend(legend_arter)
ylabel("Volume(ml)")
xlabel("Arterial pressure (mmHg)")
```



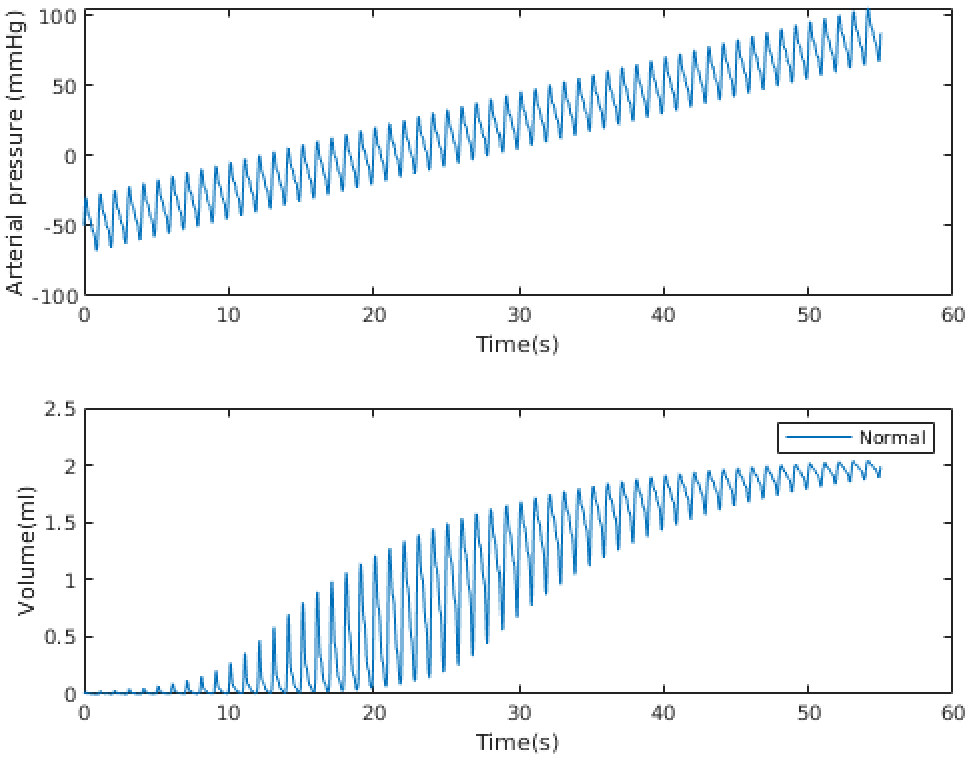
Let us now show how the transmural pressure and the volume change over time. Let us consider normal arteries first.

Excersize: Plot the graph below for different cases of arterial stifness. Explain the results.

```
j=1; % choose 1 for normal, 2 for stiff, 3 for half normal and 4 for the increased maxi
a=ArteryProp.a(j);
b=ArteryProp.b(j);
if plotting ==1
    figure
```

```
    subplot 211
    plot(t, Pt)
    xlabel("Time(s)")
    ylabel("Arterial pressure (mmHg)")
    subplot 212
    plot(t, Va(:,j))
    xlabel("Time(s)")
    ylabel("Volume(ml)")
    legend(ArteryProp.c(j));

end
```



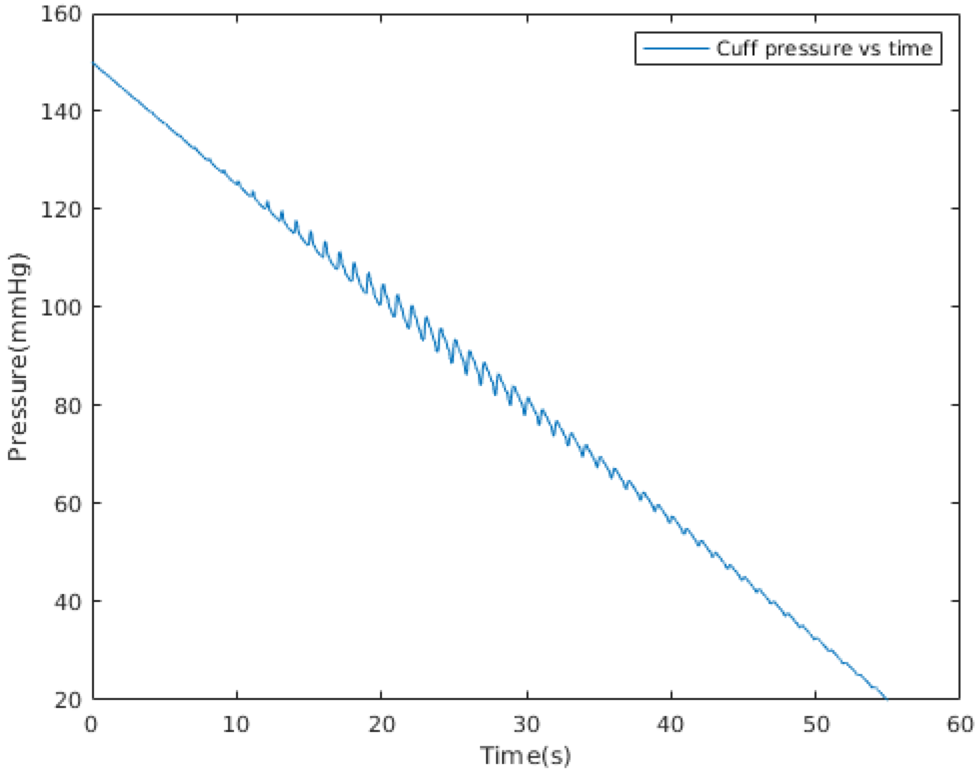
Calculation of total blood pressure in (2) is simplified version of the model presented in [1]. That model include the relationship between the changes of the total pressure and changes in the volume of the artery. Therefore, for modeling pressure signal over time using (2) please set PRESSURE_VOLUME_CHANGES=0. For modeling pressure signal using formulas (1) and (6) from [1] please set PRESSURE_VOLUME_CHANGES=1.

```
PRESSURE_VOLUME_CHANGES=0;
V0=200;     % Volume of the cuff at the beginning in ml
if PRESSURE_VOLUME_CHANGES ==1 %Pressure obtained using formulas (1) and (6) from [1]

    % dVa_dt - equation (6)
    for i=1:length(t)
        Pt(i)=Pa(i)-P0+rate*t(i); % transmural pressure
        if Pt(i)<0
            dVa_dt(i)=a*Va0*exp(a*Pt(i))*(dP_dt(i)+rate);
        else
```

```
            dVa_dt(i)=a*Va0*exp(-b*Pt(i))*(dP_dt(i)+rate);
        end
    end
    if plotting ==1
        figure; plot(P0-rate*t,dVa_dt) %plot(t,dVa_dt,'o-')
        legend('dVa/dt vs time')
    end
    P(1)=P0;
    Int_Va(1)=0;
    j=1;
    for i=2:length(t)
        P(i)=P(i-1)-rate*delta_T+delta_T*(dVa_dt(i)*(P0+760-rate*delta_T)/V0);
        %P(i)=P0-rate*t(i)+(Va(i,j)*(P0+760-rate*t(i))/V0);
    end
else %Pressure obtained using formula (2)
    % Obtaining cuff pressure with the arterial pulse - equation (1a)
    P(1)=P0;
    Int_Va(1)=0;
    j=1;
    for i=2:length(t)
        P(i)=P0-rate*t(i)+(Va(i,j)*(P0+760-rate*t(i))/V0);
    end
end

if plotting ==1
    figure,
    plot(t,P) % and another way is manual integration
    legend('Cuff pressure vs time')
     xlabel("Time(s)"), ylabel("Pressure(mmHg)")
end
```



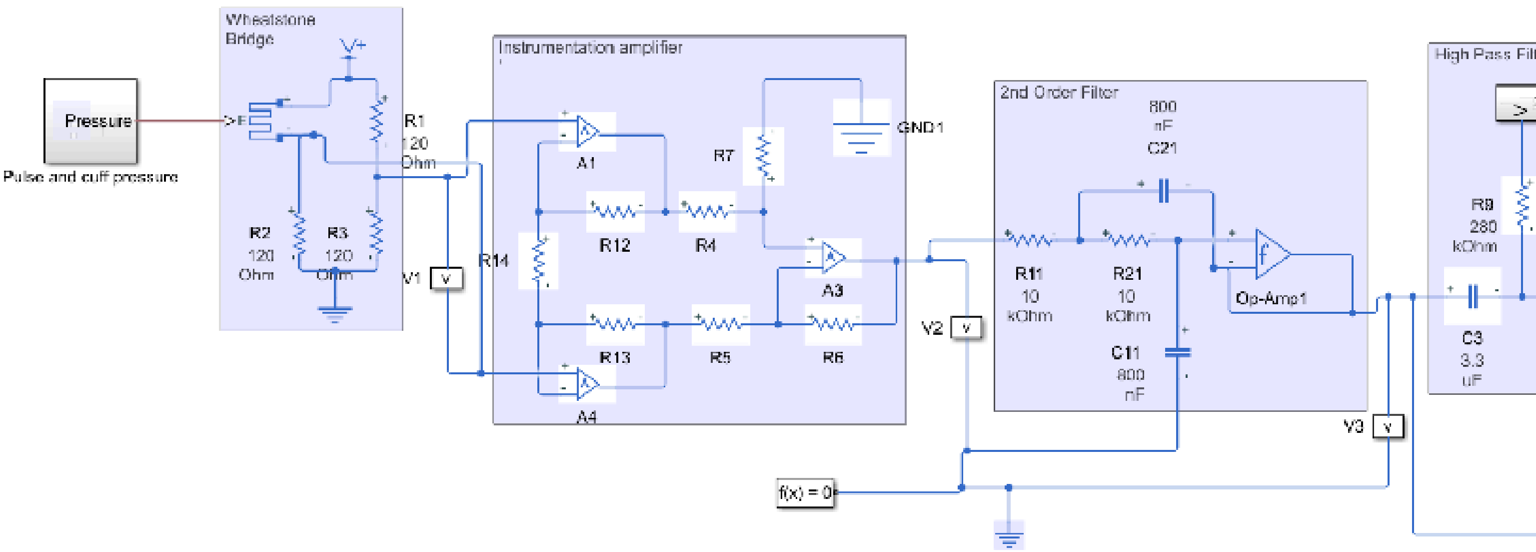
Circuit

The circuit is shown in the figure below. Please note that the motor and the cuff are not modeled. Blood pressure and cuff pressure are obtained from the simulation that has just been done.

The bridge resistance is 120 Ω. For the maximum voltage at the output of the bridge of 20 mV, we can see that the maximum change in the resistance is 1.94 Ω. Here, $V_+ = 5V$ and all operational amplifiers and the A/D converters operate in the range of 0 V to 5 V. Maximum strain that can be then applied to this strain gauge is $\varepsilon = \Delta \mathrm{R}/\mathrm{RG} = 0.0081$ where G is the gauge factor which value is set to 2. Therefore, in order to model the sensor, we converted the pressure at the input into the strain using linear transformation. The output of the Wheatstone bridge is connected to the instrumentation amplifier that amplifies the signal 100 times. This amplifier is connected to a second order low-pass filter with the cutoff frequency of 14.1 Hz. At this stage, the cuff pressure is acquired and digitized using an A/D converter ADC2. A/D converters are set to 12 bits and the sampling rate of 200 samples/s.

Oscillometric signal is further extracted by using a high-pass filter that removed the frequencies below 0.17 Hz. Therefore, this filter removed the cuff pressure and the remaining signal is the oscillometric waveform. The filter is implemented in a way so that the oscillometric waveform is centered around It needs to be amplified and filtered further. For that, an active low pass filter is used. Components and are selected to achieve Hz.

The gain of the filter at the DC level is 60. The output oscillometric signal is sampled at the same sampling rate using ADC1.




```
Psim(:,1)=0:delta_T:55;
Psim(:,2)=3.2520e-05*P; % Max input strain that will result in deltaR=0.2484 kOhm for t
                        % is 0.0081. Max pressure of 250mmH should correspond to
                        % 0.0081. Therefore, multiply pressure with 0.0081/250
open_system('BloodPressure_ADC1')
simOut = sim('BloodPressure_ADC1', 'CaptureErrors', 'on');
cp_adc=resample(simOut.CuffPressure.Data,1,5)';
omw_adc=resample(simOut.Omw.Data,1,5)';
```

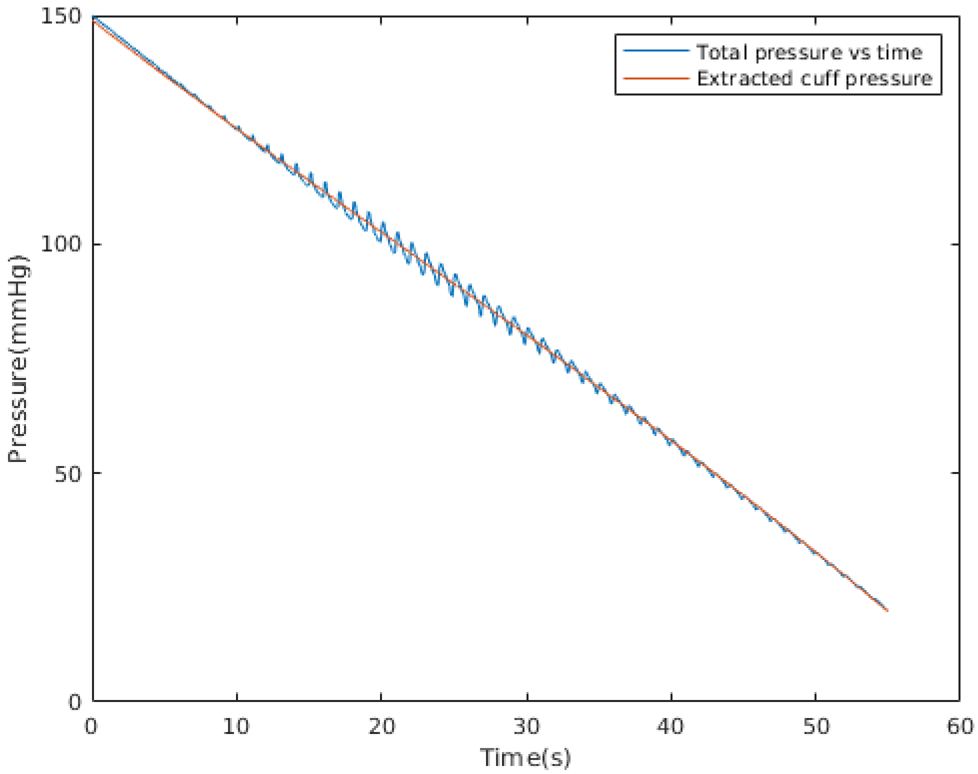
After the cuff pressure and oscillometric signals are obtained, they are in the range between 0 and $2^{12}-1=4095$. Since we need only relative values of the oscillometric pulses we do not need to rescale the signal in general. However, the cuff pressure needs to be calibrated. The coefficients for callibration are obtained by assuming that the cuff pressure sirve is linera and then taking two points from both original known cuff pressure and cp_adc obtained at the output of the ADC2.

```
% Rescale data
cp_scaled= 0.25570*cp_adc-0.4067; %.3038*(cp_adc-493)+150; %0.2291*(cp_adc-668)+150;
i=1:length(P);
f=fit(i',cp_scaled','poly3');
```

```
Warning: Equation is badly conditioned. Remove repeated data points or try centering and scaling.
```

```
cp=f(i);
if plotting ==1
```

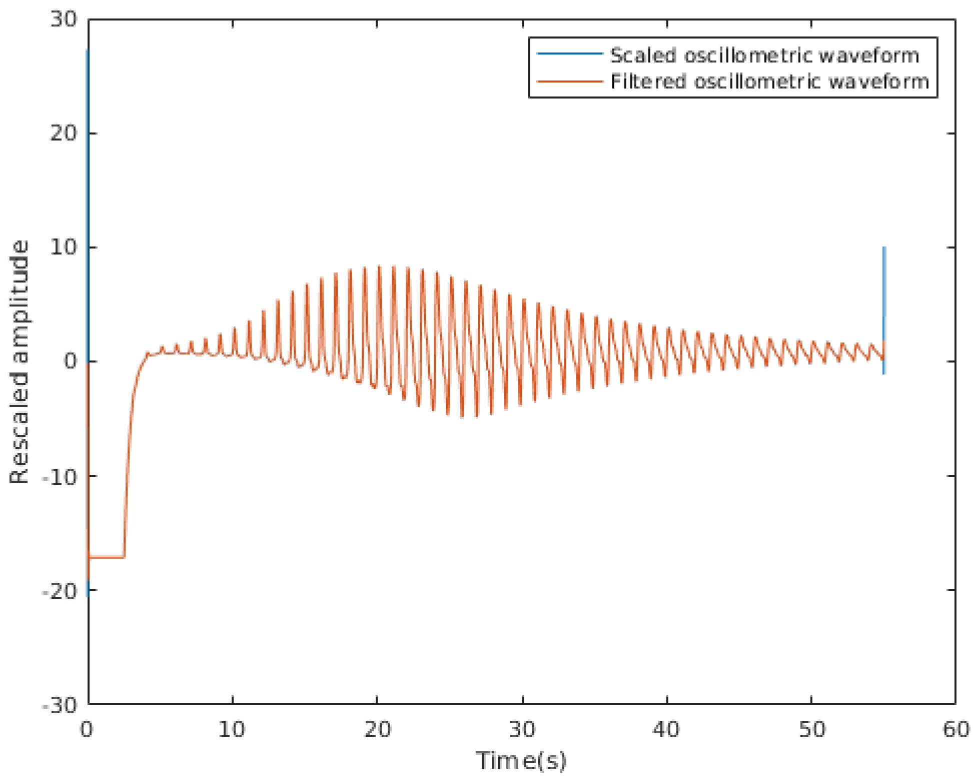
```
    figure,
    plot(t,P) % and another way is manual integration
    hold on, plot(t, cp)
    xlabel("Time(s)"), ylabel("Pressure(mmHg)"), legend('Total pressure vs time', 'Extr
end
```



In this example, oscillometric waveform is already extracted by the circuit. Next, we rescale and smooth the waweform. We can see in the figure below that scaled and filtered waveform and very similar.

```
cutoff = 10;
omw_scaled=(mean(omw_adc)-omw_adc)/100;
omw = lowpass(omw_scaled, cutoff, fs);

if plotting ==1
    figure,
    plot(t,omw_scaled-mean(omw_scaled)) % and another way is manual integration
    hold on, plot(t, omw)
    xlabel("Time(s)"), ylabel("Rescaled amplitude"), legend('Scaled oscillometric wavef
end
```



Exercise: Modify the circuit to provide only one signal at the output. Remove high-pass filter, active low pass filter and ADC1. Increase the resolution of ADC2 to 18 or 24 bits. You will also need to recalibrate the waveform at the output since it will be then in the ranle of 0 to 2^18 levels and not in the units of mmHg. Extract the oscillometric waveform from the pressure pulse algorithmically.

Oscillometric algorithms

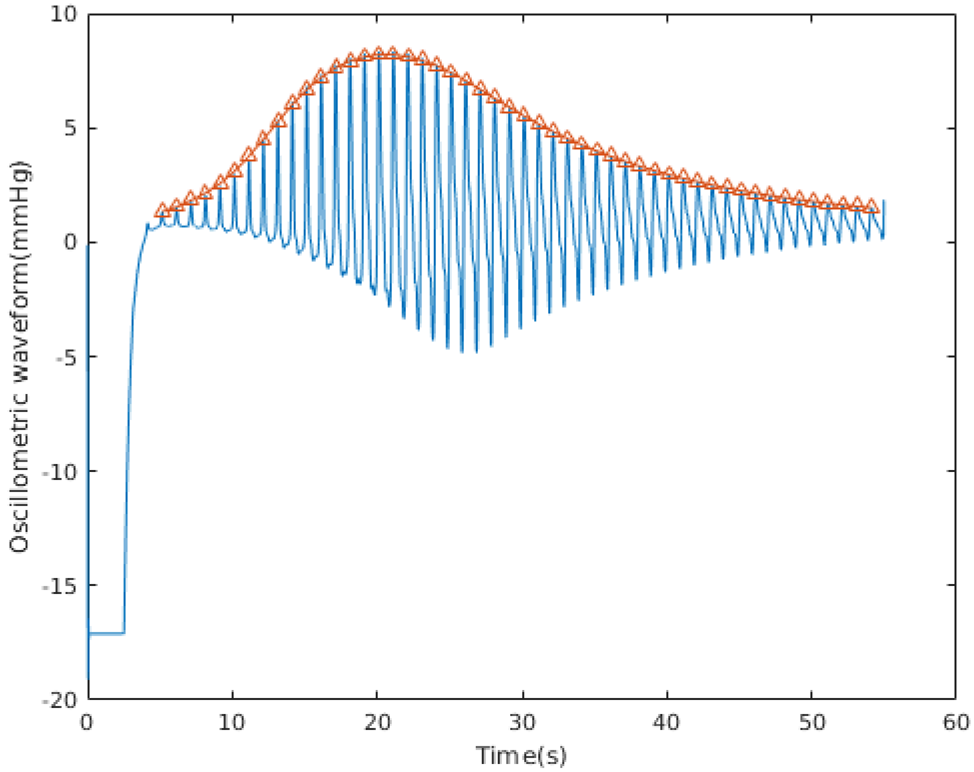
Traditional algorithm for estimating blood pressure based on oscillometric method includes several steps such as:

1. Extracting features from the pulses – these features over time are called oscillometric pulse indices (OPI).
2. Interpolating OPIs to obtain the envelope and smoothing the envelope. The envelope of an oscillating signal is defined as a smooth curve outlining its extremes.
3. Estimating MAP, SBP and DBP using the oscillometric algorithm.

2. and 3. Next steps include estimating the envelope.

```
[omwe, peak_ind] = envelope_detection(cp, omw, fs);
if plotting ==1
    figure
    plot(t,omw)
    hold on
```

```
    plot(t(peak_ind), omwe, '^-')
    xlabel("Time(s)"), ylabel("Oscillometric waveform(mmHg)")
end
```



Exercise: Uncoment the line in the envelope detection algorithm that says "Form the envelope based only on maximums" and comment the line after "Form envelope based on peak to peak". Explore the effect of finding the envelope based only on the maximum of the pulse vs peak-to-peak.

---

4. For the last step, we will consider two algorithms:

- Maxumum amplitude algorithm that is based on fixed coeffients
- Maximum slope algorithm which estimate is based on the position of the maximum slope on the diastolic and systolic part of the oscillometric envelope.

Maximum amplitude algorithm (MAA)

MAA is based on finding the time instant of the maximum of the envelope and then mapping the time instant to the cuff deflation waveform and reading the MAP. This is shown in the figure below. The time instance of SBP is obtained by finding a position on the oscilometric envelope where the maximum of the oscillometric envelope multiplied with the pre-defined coefficient intercepts the oscillometric envelope. Then, this maximum is mapped to the cuff pressure curve. Similar procedure is performed for finding diastolic presure.

```
coef(1)=0.65;
coef(2)=0.61;
[BP] = bp_max_amplitude(cp, coef, fs, omwe, peak_ind);
fprintf('Maximum amplitude algorithm')
```

```
Maximum amplitude algorithm
```

```
fprintf('SBP=%f, SBP Error=%f', BP(1), BP(1)-SBP)
```

```
SBP=115.790181, SBP Error=-4.209819
```

```
fprintf('DBP=%f, DBP Error=%f', BP(2), BP(2)-DBP)
```

```
DBP=77.605803, DBP Error=-2.394197
```

```
fprintf('MAP=%f, MAP Error=%f', BP(3), BP(3)-mean(Pa))
```

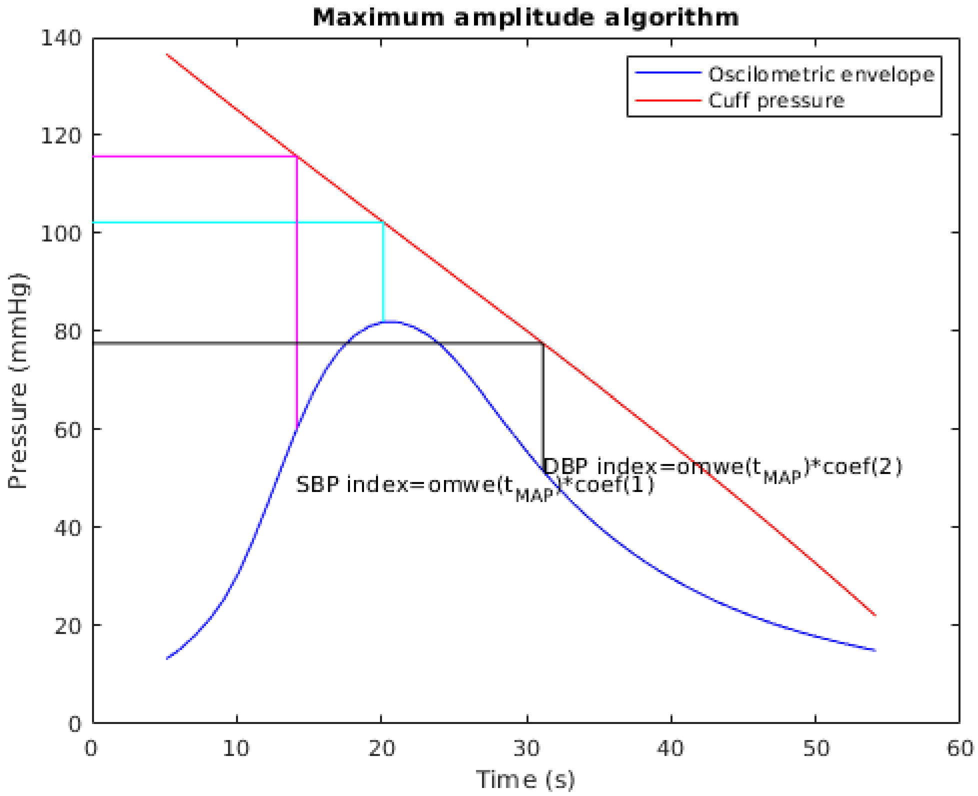
```
MAP=102.291327, MAP Error=2.291327
```

```
if plotting ==1
    [m,ind]=max(omwe);
    i1=find(m*coef(1)<omwe);
    i2=find(m*coef(2)<omwe);

    figure
    tspan = 1/fs:1/fs:length(cp)/fs;
    a1=plot(tspan(peak_ind),omwe*10, 'b'); % we are just rescaling the envelope so that
    hold on
    a2=plot(tspan(peak_ind),cp(peak_ind), 'r');
    a3=plot([0 tspan(peak_ind(ind))],[BP(3) BP(3)], 'c');
    plot([tspan(peak_ind(ind)) tspan(peak_ind(ind))],[omwe(ind)*10 BP(3)], 'c')

    a4=plot([0 tspan(peak_ind(i1(1)))],[BP(1) BP(1)], 'm');
    plot([tspan(peak_ind(i1(1))) tspan(peak_ind(i1(1)))],[omwe(i1(1))*10 BP(1)], 'm')
    text(tspan(peak_ind(i1(1))), omwe(i1(1))*8, "SBP index=omwe(t_{MAP})*coef(1)")

    a5=plot([0 tspan(peak_ind(i2(end)))],[BP(2) BP(2)], 'k');
    plot([tspan(peak_ind(i2(end))) tspan(peak_ind(i2(end)))],[omwe(i2(end))*10 BP(2)],
    text(tspan(peak_ind(i2(end))), omwe(i2(end))*10, "DBP index=omwe(t_{MAP})*coef(2)")
    xlabel('Time (s)')
    ylabel('Pressure (mmHg)')
    legend('Oscilometric envelope', 'Cuff pressure')
    title('Maximum amplitude algorithm')
end
```



Maximum Slope algorithm (MSE)

Unlike the previous algorithm, the maximum slope algorithm considers the slope of the envelope rather than the heights. Here, the systolic point is found as the point on the envelope where the slope of the envelope is at its maximum and the diastolic point is where the slope of the envelope is at its minimum. These two points can be found by taking the derivative of the signal. Since the derivative represents the slope of the line tangent to each point on the signal, the point where slope is maximum also correspond to the maximum of the derivative signal and the point where slope is minimum also corresponds to the minimum of the derivative signal.

```
[BP, index] = bp_max_slope(cp, fs, omwe, peak_ind);
fprintf('Maximum slope algorithm')
```

```
Maximum slope algorithm
```

```
fprintf('SBP=%f, SBP Error=%f', BP(1), BP(1)-SBP)
```

```
SBP=118.052307, SBP Error=-1.947693
```

```
fprintf('DBP=%f, DBP Error=%f', BP(2), BP(2)-DBP)
```

```
DBP=82.126579, DBP Error=2.126579
```

```
fprintf('MAP=%f, MAP Error=%f', BP(3), BP(3)-mean(Pa))
```

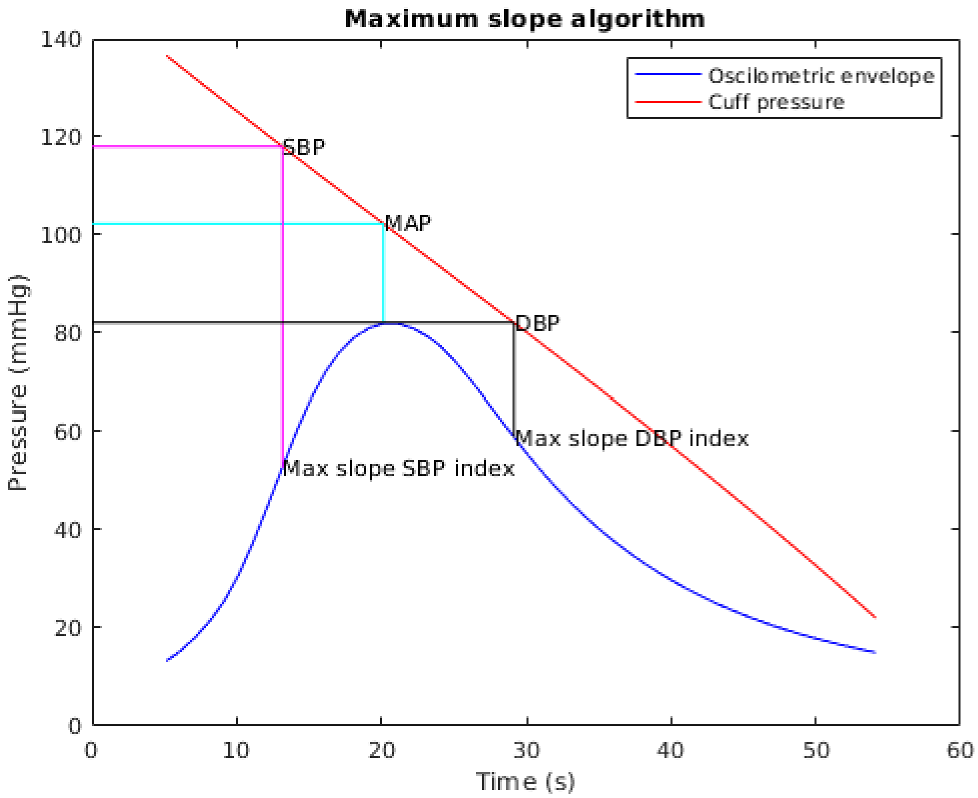
```
MAP=102.291327, MAP Error=2.291327
```

```
if plotting ==1
    figure
    tspan = 1/fs:1/fs:length(cp)/fs;
    a1=plot(tspan(peak_ind),omwe*10, 'b'); % we are just rescaling the envelope so that
    hold on
    a2=plot(tspan(peak_ind),cp(peak_ind), 'r');
    a3=plot([0 tspan(peak_ind(index(3)))],[BP(3) BP(3)], 'c');
    plot([tspan(peak_ind(index(3))) tspan(peak_ind(index(3)))],[omwe(index(3))*10 BP(3)
    text(tspan(peak_ind(index(3))), BP(3), "MAP")

    a4=plot([0 tspan(peak_ind(index(1)))],[BP(1) BP(1)], 'm');
    plot([tspan(peak_ind(index(1))) tspan(peak_ind(index(1)))],[omwe(index(1))*10 BP(1)
    text(tspan(peak_ind(index(1))), BP(1), "SBP")
    text(tspan(peak_ind(index(1))), omwe(index(1))*10, "Max slope SBP index")

    a5=plot([0 tspan(peak_ind(index(2)))],[BP(2) BP(2)], 'k');
    plot([tspan(peak_ind(index(2))) tspan(peak_ind(index(2)))],[omwe(index(2))*10 BP(2)
    text(tspan(peak_ind(index(2))), BP(2), "DBP")
    text(tspan(peak_ind(index(2))), omwe(index(2))*10, "Max slope DBP index")

    xlabel('Time (s)')
    ylabel('Pressure (mmHg)')
    legend('Oscilometric envelope', 'Cuff pressure')
    title('Maximum slope algorithm')
end
```



Exercise: Evaluate how performance of blood pressure estimation algorithms depend on the arterial stifness. Modify the compliance parameters by changing j. What is the problem with fixed coefficients of the maximum amplitude algorithms?

Exercise: Fitting in the function extract_omw is done using third order polinomial. However, the pressure waveform seems almost linear. Explore the effects of the first order curve fitting on the results. Explore other methods for curve fitting - please see "Comparison of Algorithms for Oscillometric Blood Pressure Estimation" by Silu Chen at https://github.com/Health-Devices/CARDIAC-RESPIRATORY-MONITORING/tree/master/Blood%20Pressure

Exercise: Evaluate how motion artifacts affect blood pressure. Plot the oscilometric envelope with motion artifacts. Evaluate if the postion of motion artifacts in time affect the estimates of SBP and DBP. What happens if MAP gets estimated incorrectly - how does that affect estimates of SBP and DBP?

1. ts for generated blood pressure and complieance values. Observe the results.

Evaluating performace while varying blood pressure and compliance parameters

We will run blood pressure algorithm for 100 different values of SBP, DBP and parameters a and b. We know that compliance and blood pressure have negative correlation. We just assume some values for the negative correlation coefficient - these values can be changed after analyzing real data.

```
motion=1;
mu=[140 80 0.09 0.027];
sigma=[10^2 0.2*10*5 -0.6*10*0.02 -0.6*10*0.004; 0.2*10*5 5^2 -0.3*5*0.02 -0.3*5*0.004;
rng(125)  % For reproducibility
R = mvnrnd(mu,sigma,100);
```

```
coef(1)=0.65;
coef(2)=0.61;
for i=1:100

    [P, Pa]=model_Babbs(R(i,3),R(i,4),R(i,1),R(i,2), fs, 0);
    % motion artifacts
    if motion==1
        z=zeros(1,length(P));
        start=floor(1000+floor(7500*rand(1)));  % add motion artifact at the random pla
        z(start:start+length(motion_signal)-1)=motion_signal;
        P=P+z+0.4*randn(1,length(P));
    end
    [cp,omw] = extract_omw(P, fs);
    [omwe, peak_ind] = envelope_detection(cp, omw, fs);
    % MAA algorithm with fixed coefficients
```

```
    [BP] = bp_max_amplitude(cp, coef, fs, omwe, peak_ind);
    SBP_est_fixed(i)=BP(1);
    DBP_est_fixed(i)=BP(2);


    % Max slope algorithms
    [BP, index] = bp_max_slope(cp, fs, omwe, peak_ind);
    SBP_est_slope(i)=BP(1);
    DBP_est_slope(i)=BP(2);
end
% Compute errors for all 3 algorithms
MAE_SBP=mean(abs(SBP_est_fixed-R(:,1)'));
STD_SBP=std(SBP_est_fixed-R(:,1)');
MAE_DBP=mean(abs(DBP_est_fixed-R(:,2)'));
STD_DBP=std(DBP_est_fixed-R(:,2)');
fprintf("MAA algorithm: MAE SBP=%f, std SBP=%f, MAE DBP=%f, std DBP=%f", MAE_SBP, STD_S
```

Functions

Algorithm for extracting the oscillometric waveform from the cuff pressure

```
function [cp,omw] = extract_omw(P, fs)
% Extract OMW
i=1:length(P);
w = warning ('off','all');
f=fit(i',P','poly3');
w = warning ('on','all');
cp=f(i);
%OMW
omw1 = P - cp';
cutoff = 10;
omw = lowpass(omw1, cutoff, fs);
end
```

Two blood pressure estimation algorithms are considered

1. Extracting features from the pulses – these features over time are called oscillometric pulse indices (OPI).
2. Interpolating OPIs to obtain the envelope and smoothing the envelope. The envelope of an oscillating signal is defined as a smooth curve outlining its extremes.

```
function [omwe, peak_ind] = envelope_detection(cp, omw, fs)
clear trough_ind start_ind;
%find OMW troughs
[peak_amp, peak_ind,~,~] = findpeaks(omw, 'MinPeakDistance', fs/(1.4), 'MinPeakHeight',
peak_distance = diff(peak_ind(1:end));
start_ind=peak_ind(1:end-1);
%end_ind=peak_ind(2:end-1)+round(peak_distance/3);
end_ind=peak_ind(2:end);
```

```
for i =1:length(start_ind)
    [~, ind] = min(omw(start_ind(i):end_ind(i)));
    trough_ind(i,:) = ind + start_ind(i) - 1;
end
peak_ind(1) = [];
trough_ind(1)=[];
%fix lengths and outliers
peak_ind(end) = [];

% Form the envelope based only on maximums
omwe = omw(peak_ind);
% Form envelope based on peak to peak
%omwe = omw(peak_ind)-omw(trough_ind);
omwe=smooth(medfilt1(omwe,7));
omwe_ind = peak_ind;
end
```

Maximum amplitude algorithm

```
function [BP] = bp_max_amplitude(cp, coef, fs, omwe, peak_ind)
[m,ind]=max(omwe);
BP(3)=cp(peak_ind(ind));
% Maximum amplitude
i1=find(m*coef(1)<omwe);
BP(1)=cp(peak_ind(i1(1)));
i2=find(m*coef(2)<omwe);
BP(2)=cp(peak_ind(i2(end)));
end
```

Maximum slope algorithm

```
function [BP, index] = bp_max_slope(cp, fs, omwe, peak_ind)
[m,ind]=max(omwe);
BP(3)=cp(peak_ind(ind));
index(3)=(ind);
omwe_sm=smooth(omwe);
omwe_diff=[0; diff(omwe_sm)];
[m1, i1]=max(omwe_diff(1:ind));
BP(1)=cp(peak_ind(i1));
index(1)=(i1);
[m2, i2]=min(omwe_diff(ind:end));
BP(2)=cp(peak_ind(i2+ind-1));
index(2)=(i2+ind-1);
end
%%
```

```
function [P, Pa]=model_Babbs(a,b,SBP, DBP, fs, plotting)
% This implementation follows closely the paper:
```

```
% Oscillometric measurement of systolic and diastolic blood pressures validated in a ph
% by Charles F BabbsEmail author
% published in BioMedical Engineering OnLine, 2012, 11:56
% https://biomedical-engineering-online.biomedcentral.com/articles/10.1186/1475-925X-11


%Blood pressure to be simulated - please change systolic in the rangge 110
%to 140 and dia between 60 and 90

%%

r=0.12; % radius of the artery in cm
L=10;    % length of the artery covered by the cuff in cm
V0=200; % Volume of the cuff at the beginning in ml
delta_r=0.05; %  the brachial artery strain (?r/r) during a normal pulse is 4 percent f

%%
%Computing the parameters
PP= SBP-DBP; % pulse pressure
Pmid=0.5*(SBP+DBP); % mid pressure
P0=SBP+30; % start of cuff deflation

%a = 0.076; %log(0.1)/(-20); % stiffness coefficient change to 0.075 or 0.11 for very s
rate=2.5; %rate of the cuff defflation
heart_rate=1; % in Hz
delta_Va=2*3.14*(r)*(delta_r*r)*L; %2*pi*r*delta_r*L change in volume

Cn= delta_Va/PP; % The normal pressure compliance for the artery segment is the volume

Va0=3.14*(r)^2*L; %The resting artery volume

%b=-log(Cn/(a*Va0))/Pmid; % another stiffness coefficient - equation (3) from the paper
%b=0.021;
% Model of the arterial pulse and its derivative
delta_T=1/fs;
t=0:delta_T:55;
omega=2*pi*heart_rate;
Pa=DBP+0.5*PP+0.36*PP*(sin(omega*t)+0.5*sin(2*omega*t)+0.25*sin(3*omega*t));
dP_dt=0.36*PP*omega*(cos(omega*t)+cos(2*omega*t)+0.75*cos(3*omega*t));
%%
% Volume vs transmural pressure - equation (4) from the paper
for i=1:length(t)
    Pt(i)=Pa(i)-P0+rate*t(i);
    if Pt(i)<0
        Va(i)=Va0*exp(a*Pt(i));
    else
        Va(i)=Va0*(1+(1-exp(-b*Pt(i)))*a/b);
    end
end
if plotting ==1
    figure; plot(Pt,Va,'o')
    legend('Volume(ml) vs Transmural pressure')
end
%%
```

```
% dVa_dt - equation (6)
for i=1:length(t)
    Pt(i)=Pa(i)-P0+rate*t(i); % transmural pressure
    if Pt(i)<0
        dVa_dt(i)=a*Va0*exp(a*Pt(i))*(dP_dt(i)+rate);
    else
        dVa_dt(i)=a*Va0*exp(-b*Pt(i))*(dP_dt(i)+rate);
    end
end
if plotting ==1
    figure; plot(P0-rate*t,dVa_dt) %plot(t,dVa_dt,'o-')
    legend('dVa/dt vs time')
end
%%
% Obtaining cuff pressure with the arterial pulse - equation (1a)
P(1)=P0;
Int_Va(1)=0;
for i=2:length(t)

    P(i)=P(i-1)-rate*delta_T+delta_T*(dVa_dt(i)*(P0+760-rate*t(i))/V0);
end
tspan = 0:delta_T:t(end);
if plotting ==1
    figure,
    hold on; plot(t,P) % and another way is manual integration
    legend('Cuff pressure vs time')
end
end
%%
```