ISTANBUL TECHNICAL UNIVERSITY

FACULTY OF ELECTRICAL AND ELECTRONICS

CONTROL AND AUTOMATION ENGINEERING DEPARTMENT

KON 305E – PROGRAMMING TECHNIQUES IN CONTROL

FINAL PROJECT

TEAM 4

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Deadline

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Contents

A. CARDIOVASCULAR SYSTEM MODEL

Heart (1) & Vascular System (2) Models

a. Realize the above equations, starting from the heart model, in Simulink. Carry out a simulation by using the given parameter file (*termProjectParameters.m*) during $5\ minutes$ (to avoid transient state) and consider only the last $30\ seconds$. Plot the pressure outputs for systemic artery (P_{sa}) and pulmonary artery (P_{pa}), respectively.

ANSWER

After realizing equations in Simulink for heart model, we simulated using the given parameters during 5 minutes. The last 30 seconds, when the transient ignored, plottings for the pressure outputs for systemic artery (P_{sa}) and pulmonary artery (P_{pa}) is as in Figure A.2.

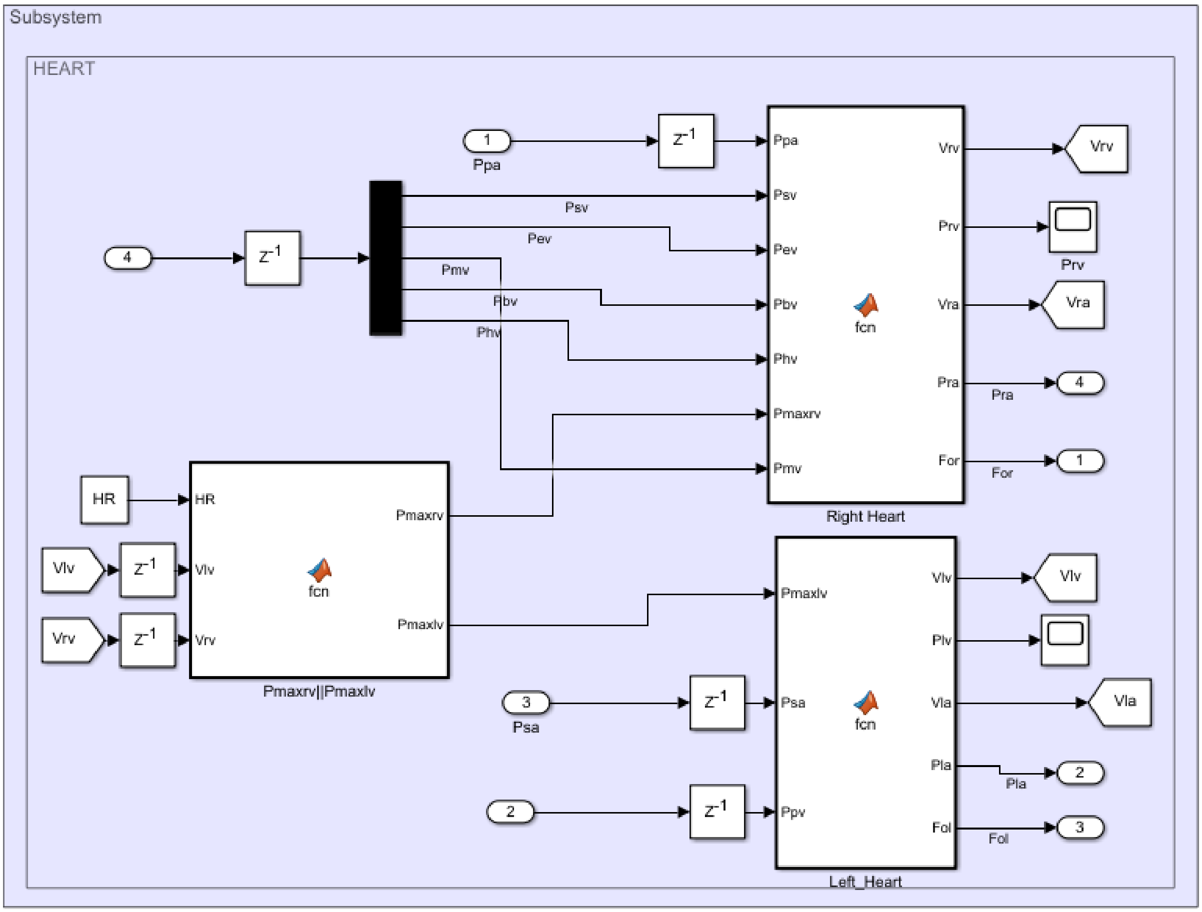

Figure A.1.

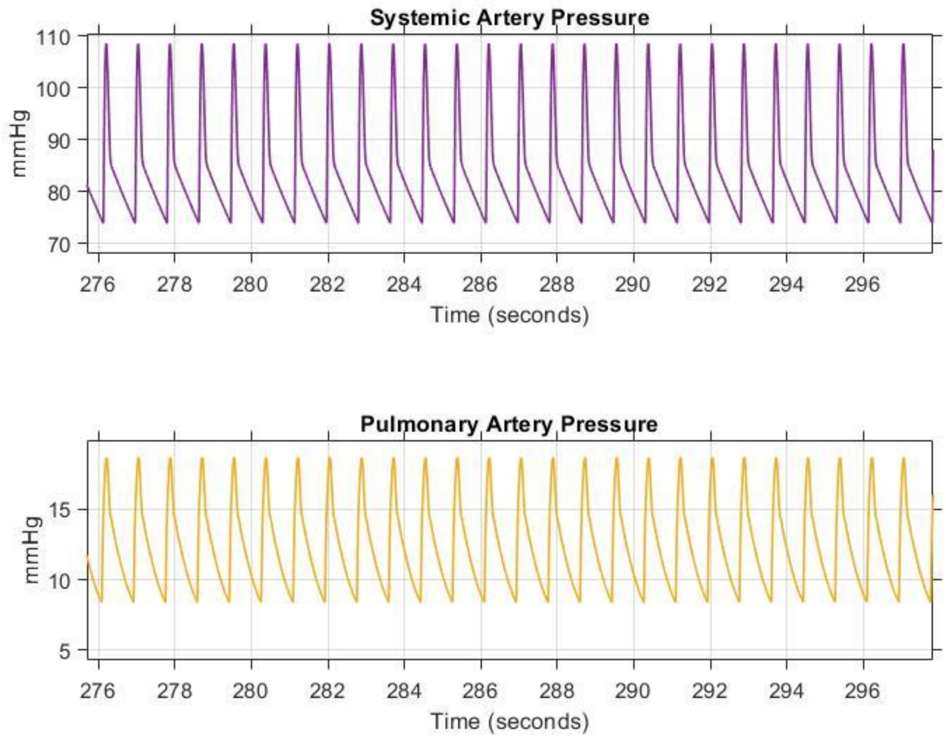

Figure A.2. Pressure Outputs For Systemic Artery (P_{sa}) and Pulmonary Artery (P_{pa})

b. You are expected to search the real pressure curves on web and compare the real data with the results you have found above.

ANSWER

Normal systemic artery pressure is $80 - 120\ mmHg$ and normal pulmonary artery pressure is $8 - 20\ mmHg$ at rest. We have also obtained approximately these values as slightly lower.

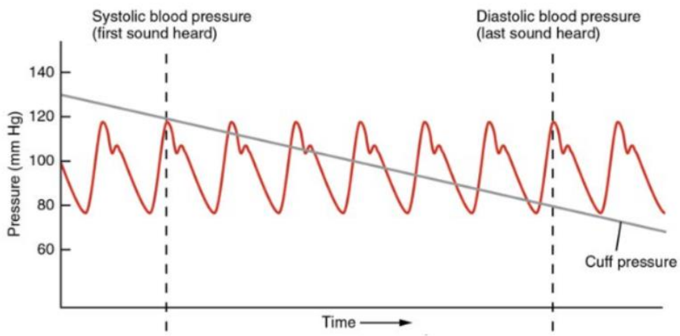

Figure A.3. Systemic Artery Pressure [1]

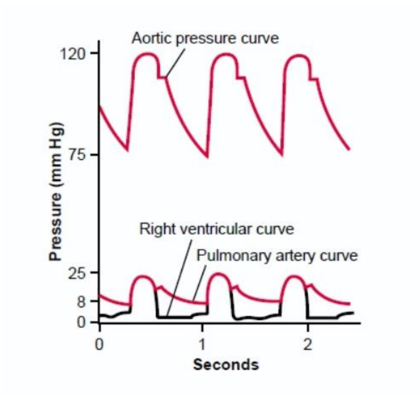

Figure A.4. Pulmonary Artery Pressure [2]

c. Plot the systemic (F_{sa}) and pulmonary (F_{pa}) blood flows. Also, calculate the average blood flow in one cycle (You can use systemic or pulmonary blood flow since they will give you nearly the same result).

ANSWER

When we plot the systemic (F_{sa}) and pulmonary (F_{pa}) blood flows, we got Figure A.7. Also, we calculated the avarage blood flow as $71.37\ mL$ in one cycle for $HR = 72$.

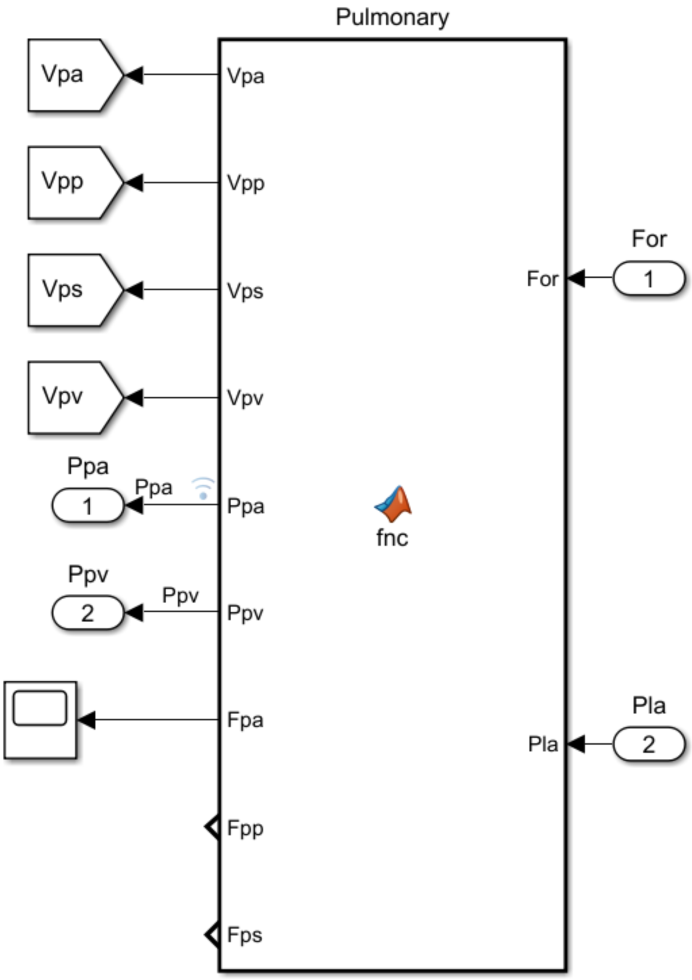

Figure A.5.

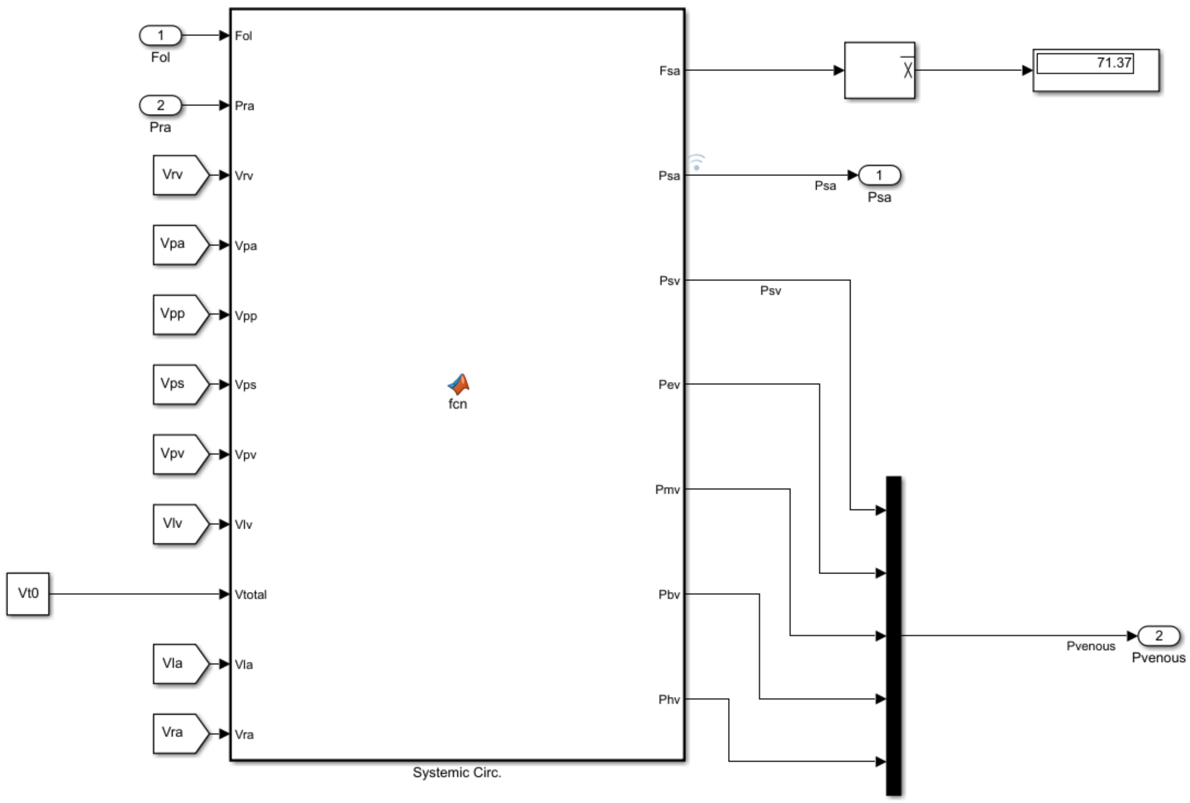

Figure A.6.

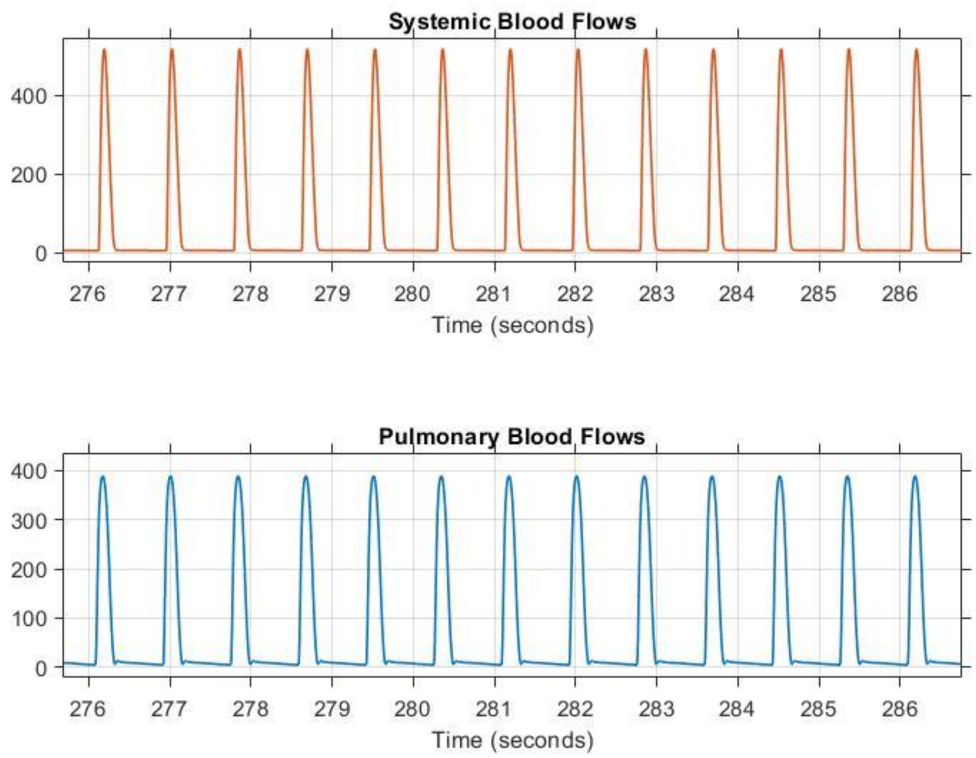

Figure A.7. Systemic (F_{sa}) and pulmonary (F_{pa}) blood flows

d. Assume that the person has lost 15% blood due to bleeding. Simulate this situation by multiplying the total blood volume and all unstressed volumes by $k = 0.85$. Plot the (systemic) blood pressure. Plot the blood pressure again by changing the heart rate as $HR = 120$ and comment on the results.

ANSWER

Assuming that the person has lost 15% blood we reduced total blood volume and all unstressed volumes. We observed the change in the (systemic) blood pressure as in Figure A.8. The decrease in blood volume also resulted in decrease in blood pressure.

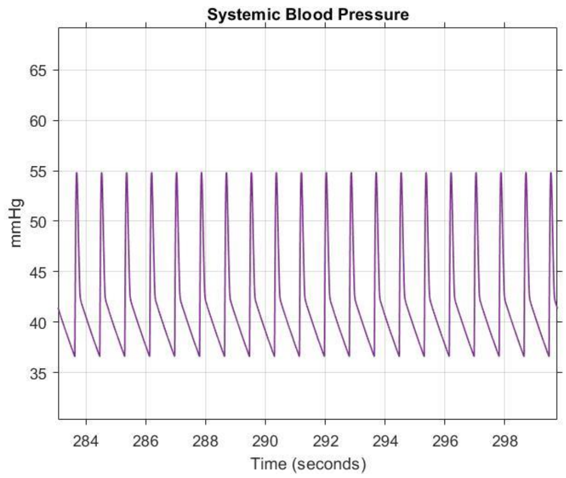

Figure A.8.

In the same state, we changed the heart rate as $HR = 120$ instead of 72. As seen in Figure A.9., an increase in heart rate caused an increase in blood pressure. But this increase is quite small compared to the decrease in blood pressure caused by blood loss.

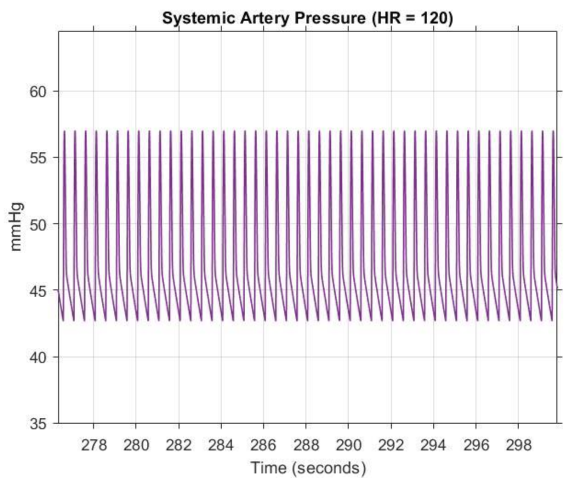

Figure A.9.

B. RESPIRATORY SYSTEM MODEL

Lung Mechanics Model (1)

a. Construct the above electrical circuit in Simulink with the help of the Simscape library. Find the transfer function between the input ($P_{mus}(s)$ and output ($V'(s)$with the help of linear analysis toolbox (choose a continuous solver at this step).

ANSWER

We need to create our circuit with the help of Simscape Electical Library in Simulink. We will choose $P_{mus}(s)$ as a controlled voltage source which its detailed information about this given in section b. So, considering these, we can create the circuit as below:

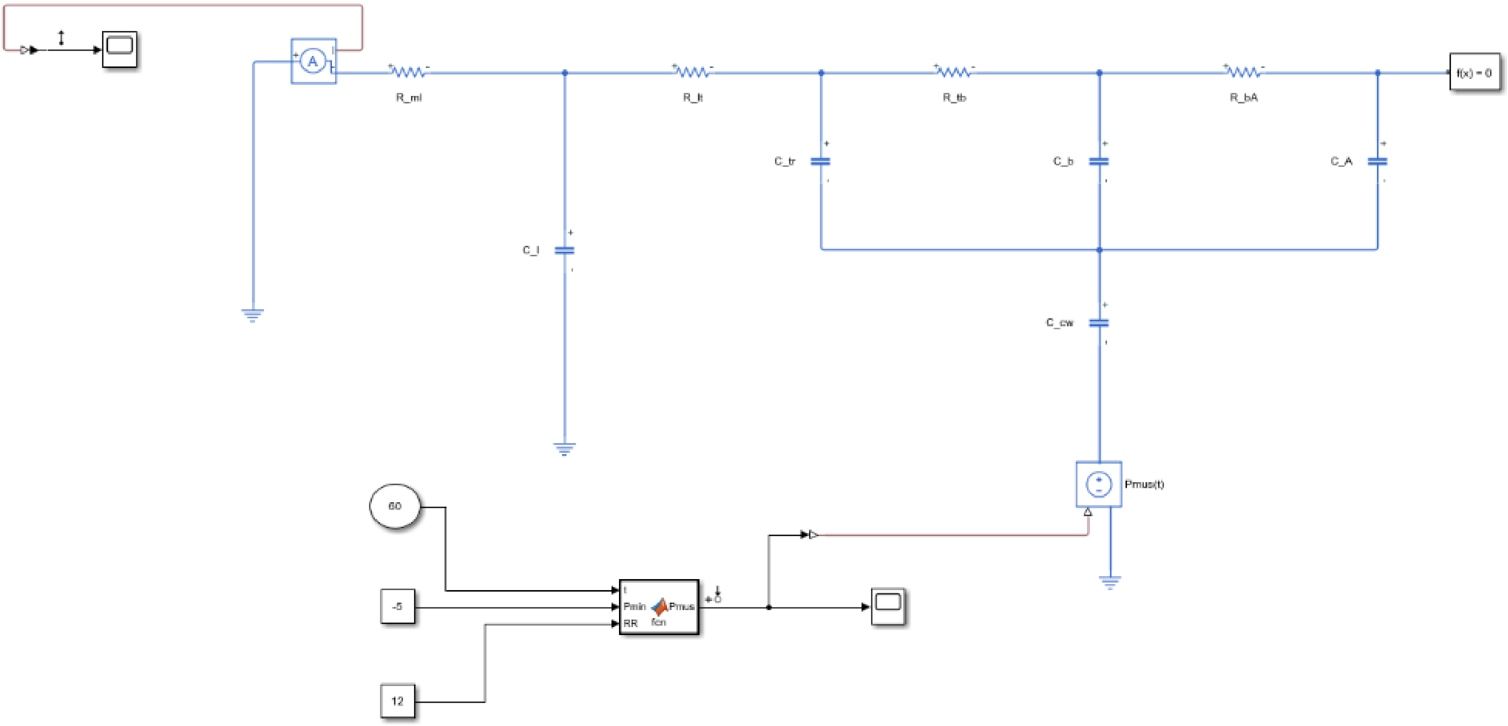

Figure B.1.1. Circuit Model

Details about the Matlab function block will be given in the section c. We used these additional blocks (Current Sensor, Matlab Function etc.) to be able to obtain the transfer function with the help of the Linear Analysis Toolbox. If we choose P_{mus}, the output of the Matlab function block, as input perturbation and the input signal of current sensor's scope as output measurement (which is wanted in the question and which you can see above), we can obtain the transfer function below via Linear Analysis Toolbox.

```
Linearization Result:

  From input "u1" to output "y1":
          -2289 s^3 - 6.01e06 s^2 - 3.193e09 s
  ----------------------------------------------------
  s^4 + 6996 s^3 + 1.213e07 s^2 + 5.615e09 s + 3.273e10

Name: Linearization at model initial condition
Continuous-time transfer function.
```

Figure B.1.2. Obtained Transfer Function

We can also obtain the scope outputs of Matlab function and current sensor blocks, as below, for better understanding of the problem.

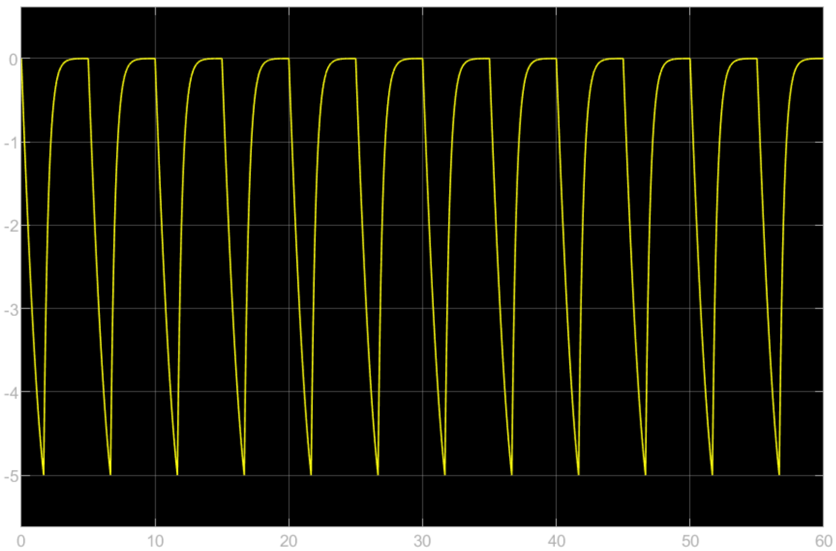

Figure B.1.3. Scope Output of the Matlab Function Block

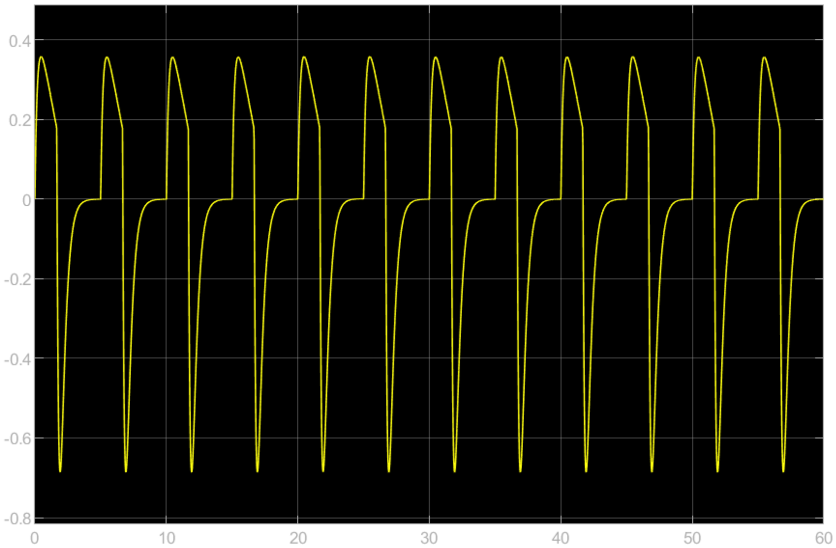

Figure B.1.4. Scope Output of the Current Sensor Block

b. Pressure equation provided by respiratory muscles is given.

ANSWER

In this section, pressure equation provided by respiratory muscles is given. We need to create a Matlab code to be able to obtain the specified periodic signal. We can write the code below, which contains all the equations in this section. We will get help from this code below, in the next sections.

```
function[P_mus] = fnc(P_min, RR)
t=0:0.01:60;
IE_ratio = 1/2;
T = (60/RR);
T_e = T/(IE_ratio + 1);
T_i = IE_ratio * T_e;
Tau = T_e/10;
for i=1:6001
    if (rem(t(i),T)) < T_i
        u(i)=P_min*(T*rem(t(i),T)-
rem(t(i),T)^2)/(T_i*T_e);
    end
    if (rem(t(i),T)) >= T_i
        u(i)=P_min*(exp(-(rem(t(i),T)-T_i)/Tau)-exp(-
T_e/Tau))/(1-exp(-T_e/Tau));
    end
end

plot(t,u)
xlabel('Time (s)');
ylabel('Output Periodic Signal');
title('P_mus(t)');
P_mus = u;
end
```

After running this code above, we also need to write these lines into the command line to obtain the output periodic signal.

```
>> Pmin = -5; RR = 12;
```

```
>> fnc(P_min, RR)
```

Then, we can obtain the plot which is shown below.

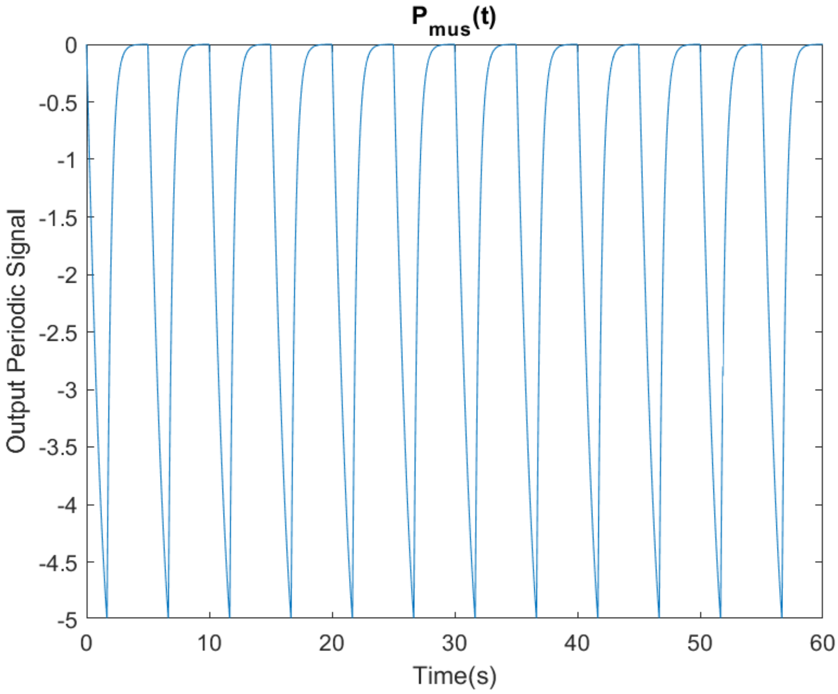

Figure B.1.5. Obtained Output of $P_{mus}(s)$

After obtaining this output, we can realize that ***Figure B.1.3.*** and ***Figure B.1.5.*** are the same. So, this means our circuit model gives us pretty good results.

c. Create a MATLAB function in Simulink which has one output ($P_{mus}(t)$) and two inputs /P_{min} *and* RR)) in order to produce the specified periodic signal. Connect the output of this function to the electrical circuit via controlled voltage source and plot the muscle pressure, airflow $V'(t)$ and tidal volume ($V_T(t)$), which is given as, $V_T(t) = \int V'(t)dt$ on the same figure by taking $P_{min} = P_{min0}$ and $RR = RR_0$.

Compared to section a, we need to add a new component to observe the airflow and tidal volume while the main structure will stay the same. Before observing these, firstly, we wanted to share the code from the Matlab Function block, as below.

```
function P_mus = fcn(t, P_min, RR)
IE_ratio = 1/2;
T = (60/RR);
T_e = T / (IE_ratio + 1);
T_i = IE_ratio * Te;
tau=T_e/10;
if (rem(t,T)) < T_i
u=P_min*(T*rem(t,T)-rem(t,T)^2)/(T_i*T_e);
else
```

```
u=P_min*(exp(-(rem(t,T)-T_i)/tau)-exp(-T_e/tau))/(1-exp(-T_e/tau));
end
P_mus = u;
end
```

Now, we are ready to update our circuit model to add a new block called "Integrator Limited". This helps us to obtain the $\boldsymbol{V_T(t)}$.

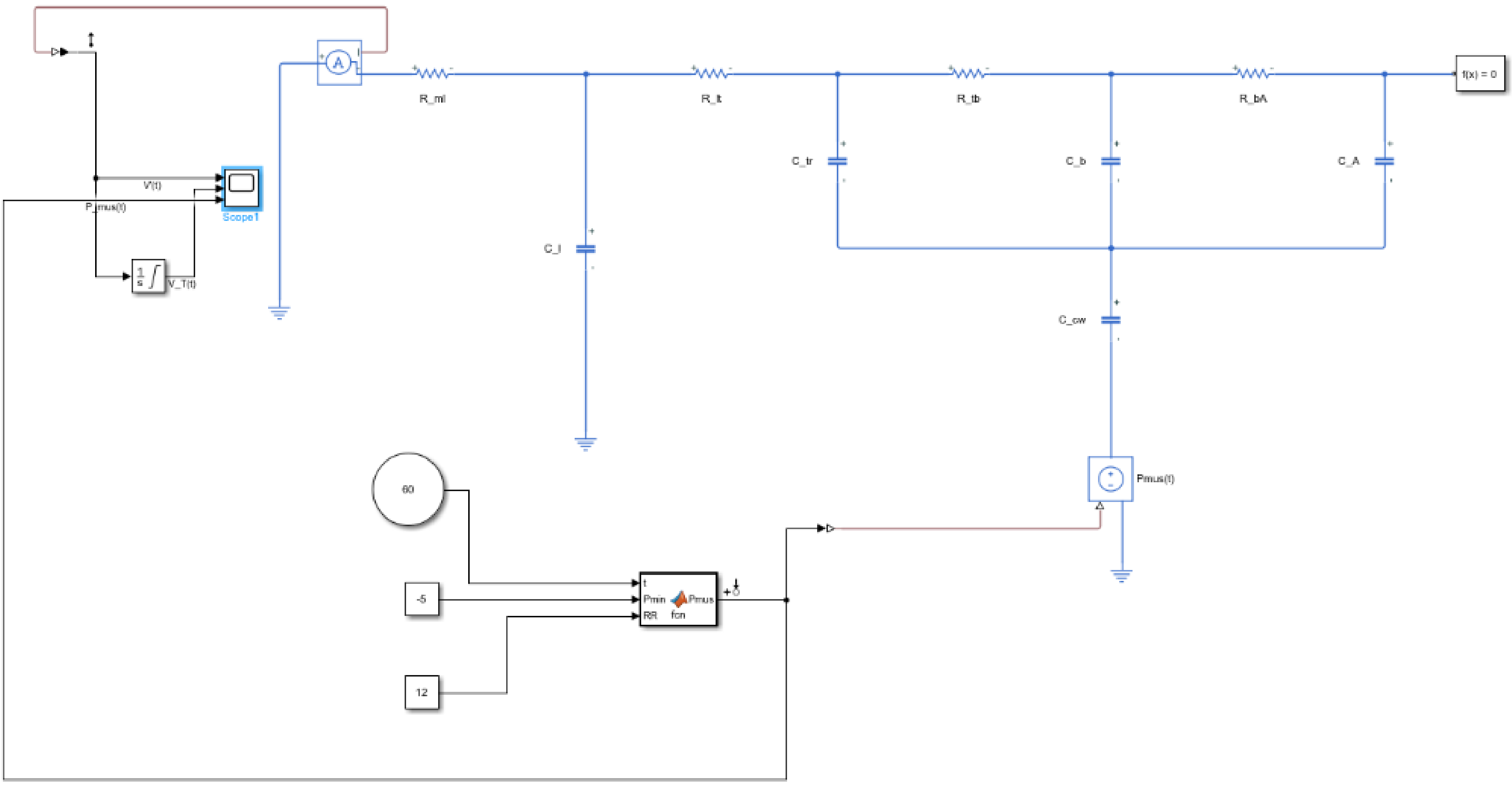

Figure B.1.6. Updated Model Circuit

As we can realize, the only difference with the ***Figure B.1.1.*** is one "Integrator Limited" block added to the scope of the current sensor. And, we also brought Matlab Function block's output into the scope of the current sensor to be able to obtain all the signals in a subplot. Before running this, we need to point out that we set the step size as 0.00001 and clock block's decimation as 5 since the C_{tr} capacitor has 5 decimal digits. Now, we are ready to obtain the subplots, as below.

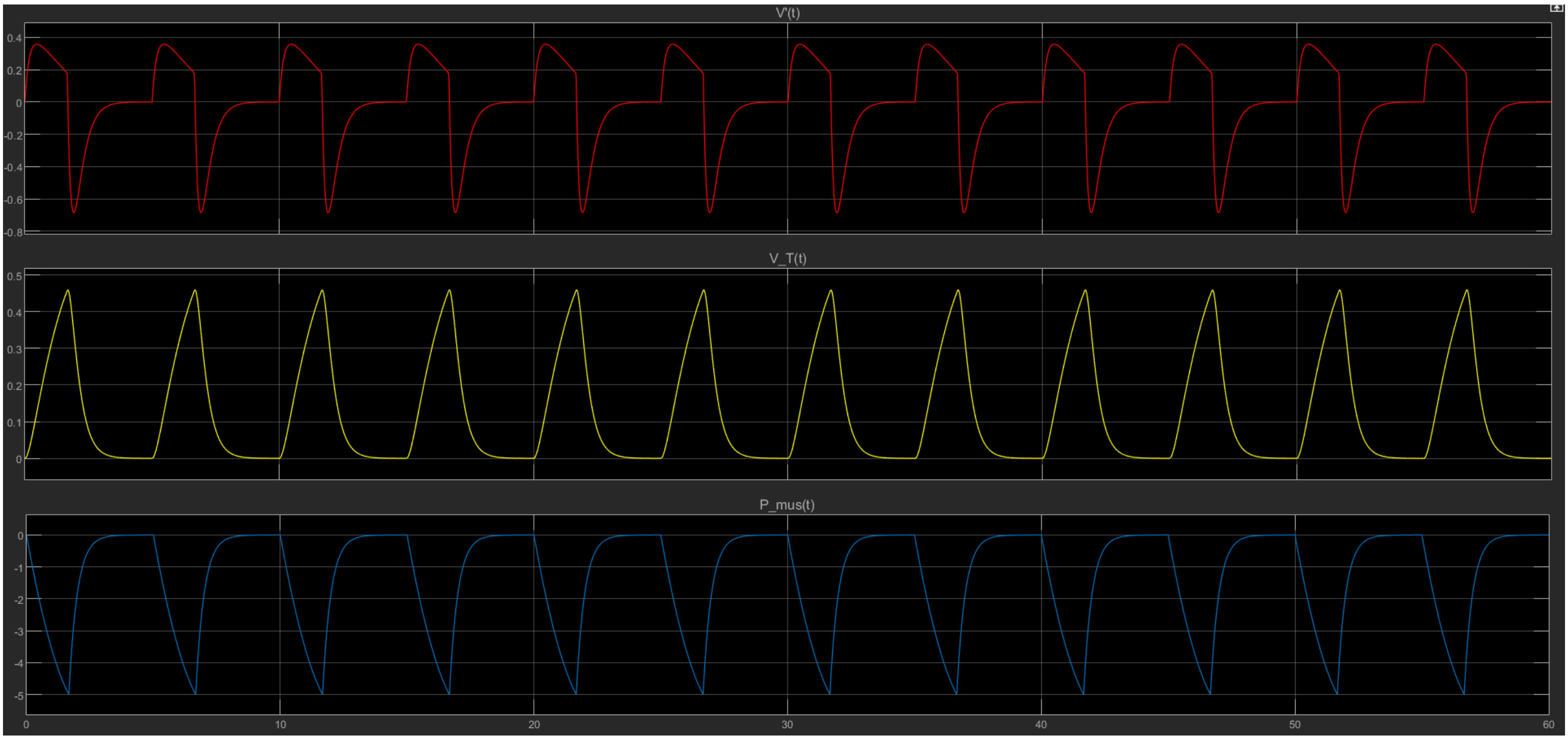

Figure B.1.7. Obtained Subplots

In this subplot, red signal represents the airflow ($V'(t)$), yellow signal represents the tidal volume ($V_T(t)$) and blue signal represents the muscles pressure ($P_{mus}(t)$).

d. Verify the transfer function you have found by applying the same periodic input signal ($P_{mus}(t)$) to the transfer function (you must obtain the same airflow and tidal volume outputs).

We need to verify the results that we obtained in previous sections. To do this, we need to create another block diagram in the Simulink environment, connecting the same signal and transfer function. You can see the diagram that we mentioned, in below.

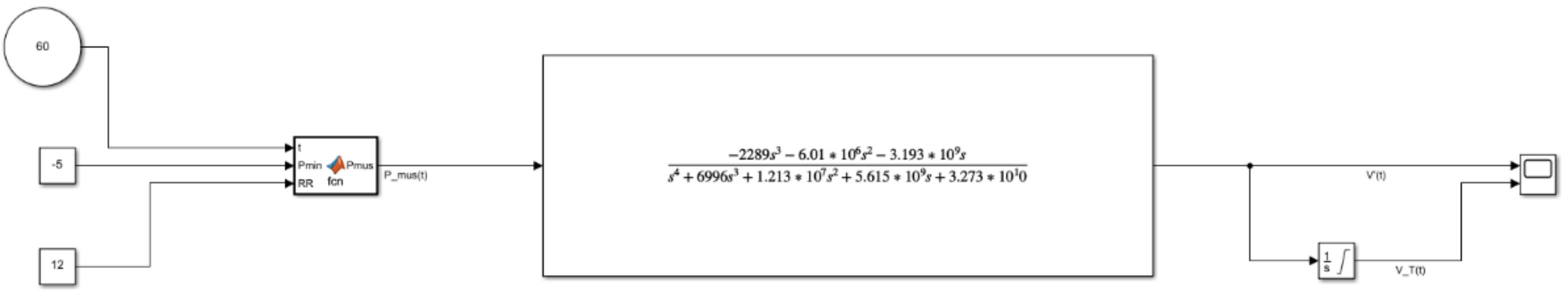

Figure B.1.8. Designed Block Diagram

When we run the system above, we can obtain the subplot below.

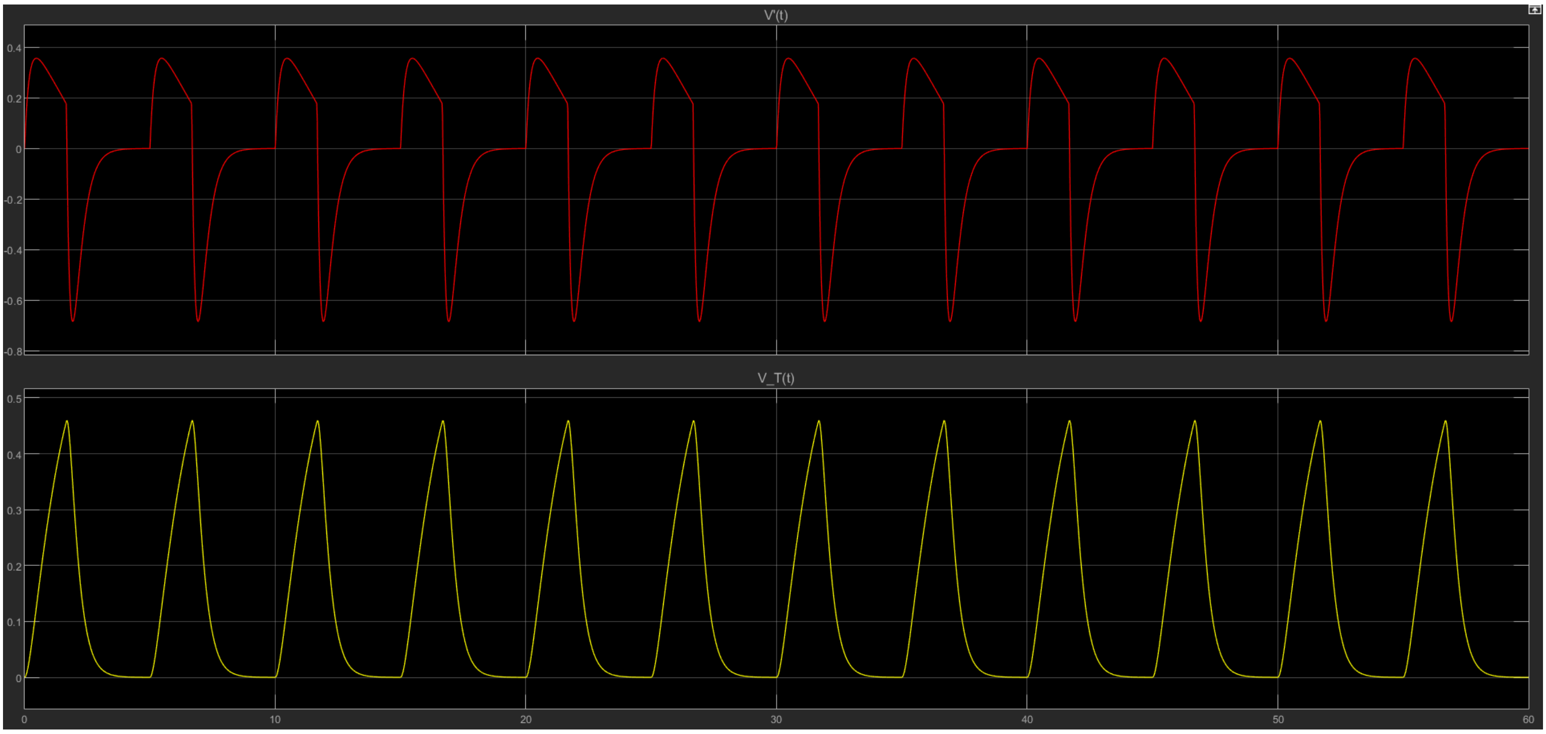

Figure B.1.9. Obtained Subplots

Now, if we compare this obtained subplots with the subplots in ***Figure B.1.7.***, we can easily see that obtained airflow ($V'(t)$) and the tidal volume ($V_T(t)$) outputs are identical. So, it can be said that the transfer function that is found in section a is now verified and is calculated without an error.

Dead Space and Alveolar Gas Exchange Model (2)

a. By considering the information given above, implement the differential (and algebraic) equations related to the dead space and alveolar gas exchange in Simulink. For the tidal volume $V_T(t)$, use the output of the lung mechanics model.

Until the tissue gas exchange model is given, assume that *shunt=0* (i.e. arterial values are equal to the alveolar ones since $F_{ps} = 0$).

(*Note:* Do not forget to assign the initial conditions, such as C_{vCO_2IC}, P_{ACO_2IC} etc. to the corresponding "integrator" and "delay" elements, or persistent variables)

$C_{vCO_2} = C_{vCO_2IC}$ and $C_{vCO_2} = C_{vCO_2IC}$ values are used from the parameter file for this question.

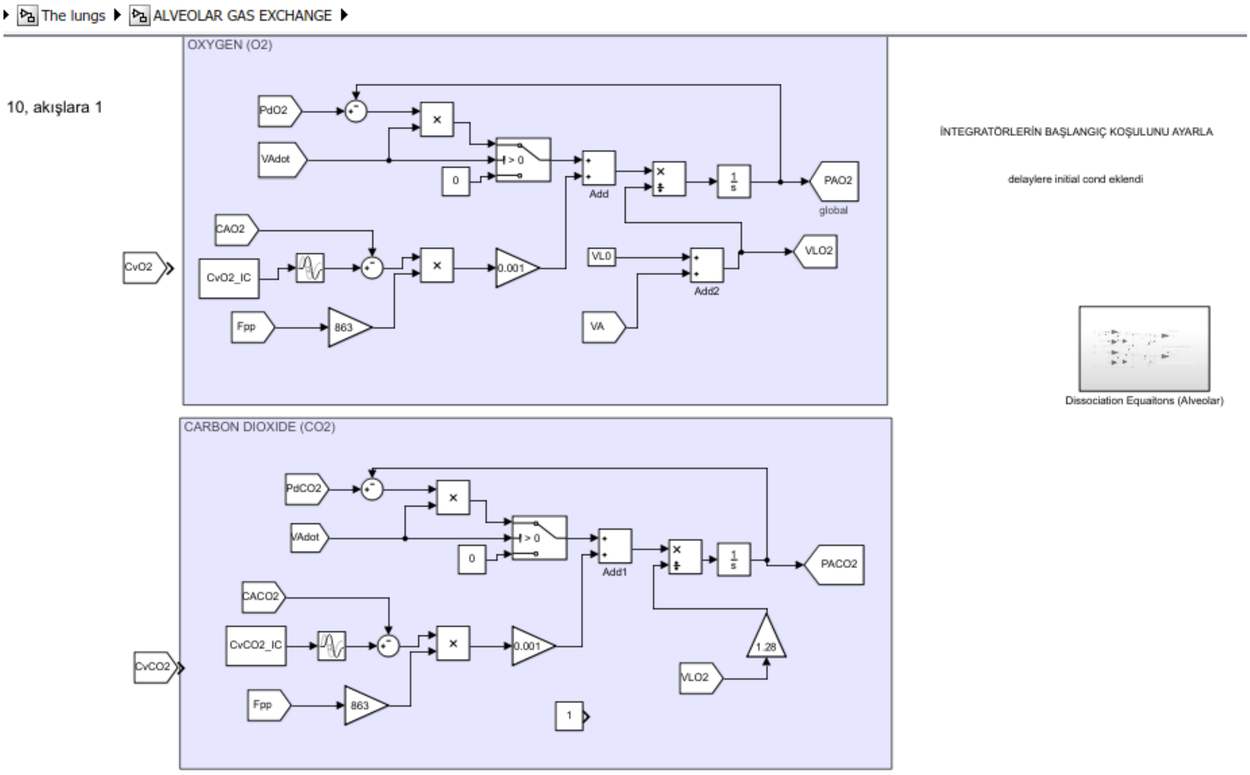

Figure B.2.1.

$Shunt = 0$ and $F_p = 75ml$ selected; we can see as above; (so, $F_{pp} = 75$, $F_{ps} = 0$.)

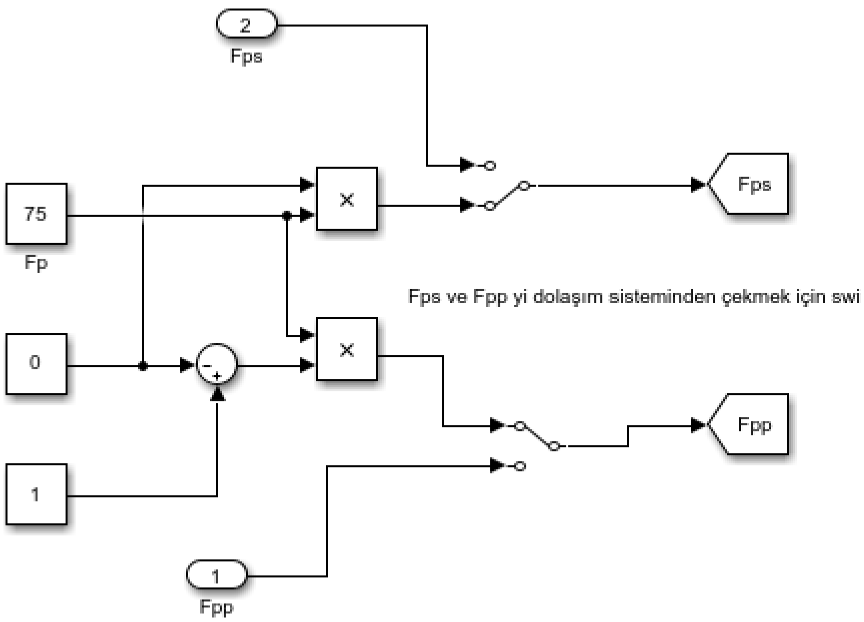

Figure B.2.2.

And we can see the arterial equations. (constantration and partial pressures):

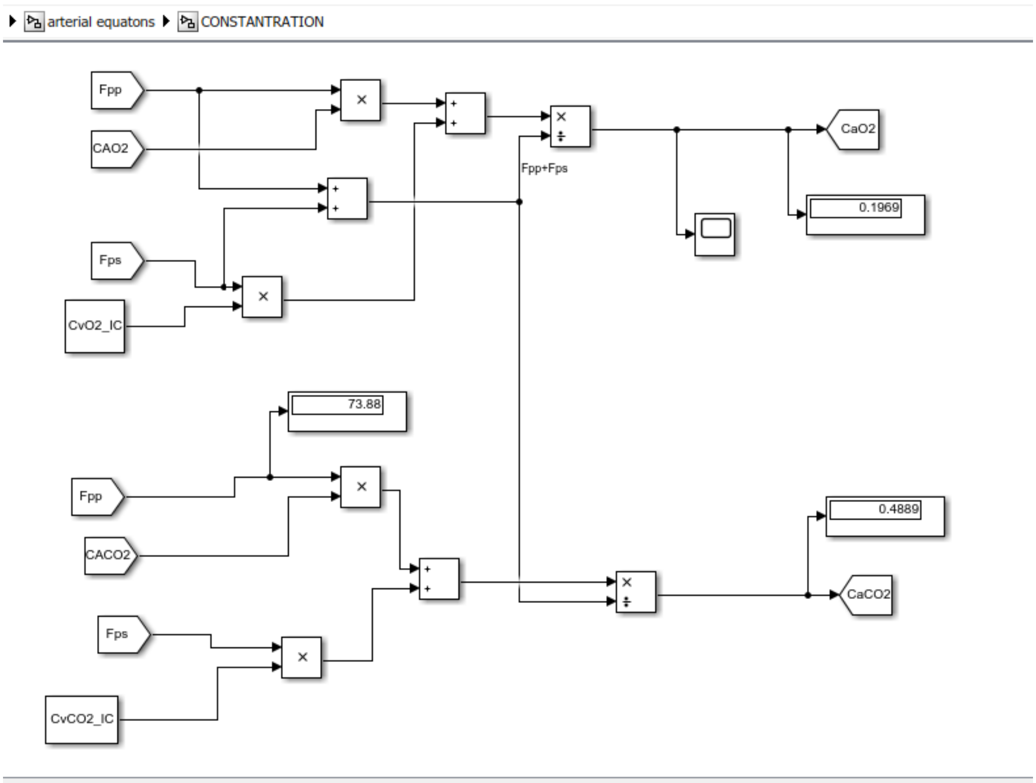

Figure B.2.3.

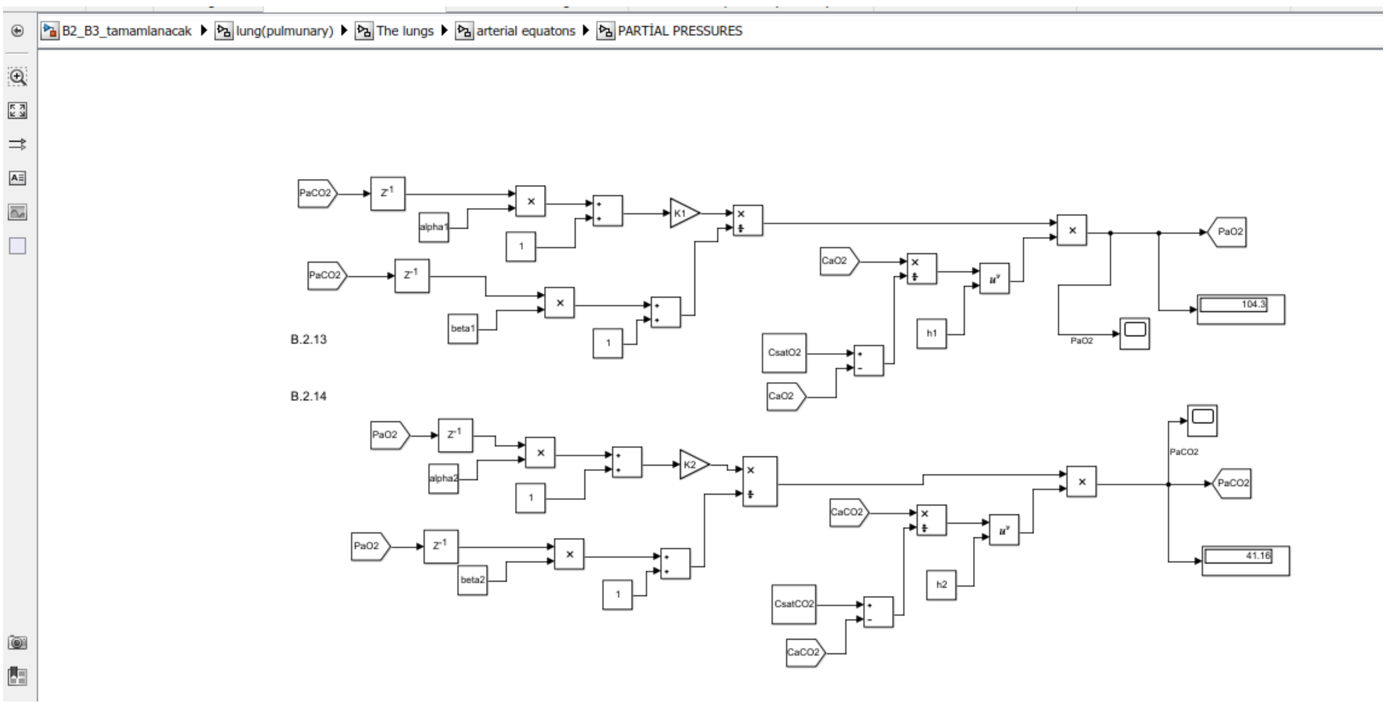

Figure B.2.4.

$Vdot$ value is taken from b.1. with go to block:

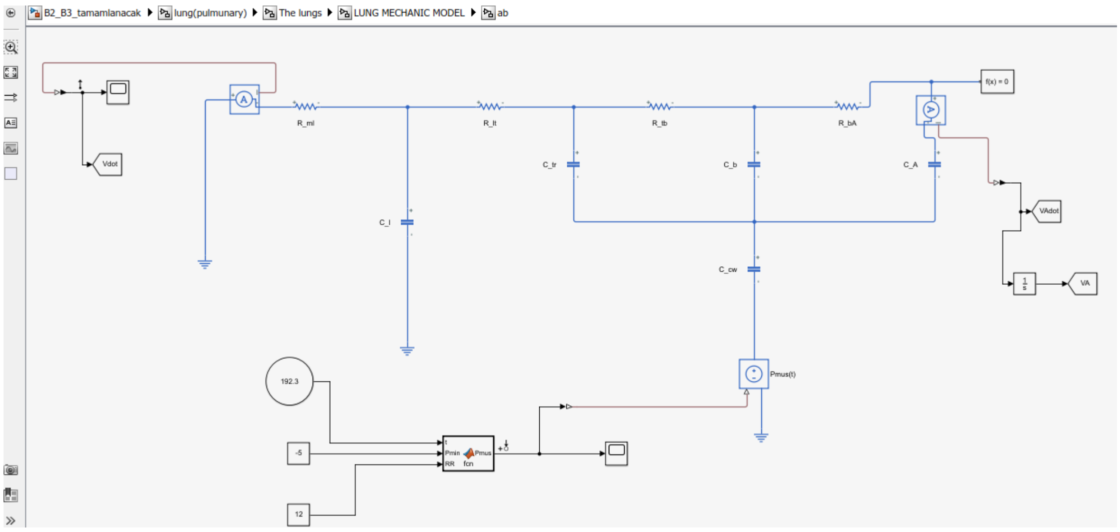

Figure B.2.5.

b. Using the parameter values, and by taking the blood flow constant as $F_p(t) = 75ml$, simulate the system during 5 minutes. Plot the partial pressure of the arterial oxygen ($P_{aO_2} = P_{AO_2}$) and arterial carbon dioxide ($P_{aCO_2} = P_{ACO_2}$) for the last 60 seconds. For a healthy subject, show that the arterial O2 and CO2 pressures are around 95 mmHg and 40 mmHg, respectively.

(*Note:* Since the tissue gas exchange is not modelled yet, take $C_{vCO_2} = C_{vCO_2 IC}$ and during the simulation).

$C_{vO_2} = C_{vO_2 IC}$ and $C_{vCO_2} = C_{vCO_2 IC}$ and $Shunt = 0$ and $F_p = 75ml$ selected. Under the these conditions, we obtain these pressures (mmHg):

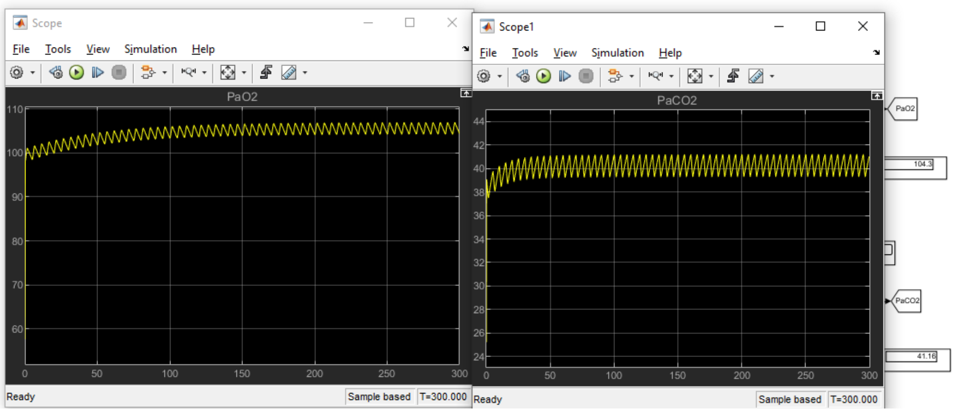

Figure B.2.6.

Partial pressure of the arterial oxygen ($PaO2 = PAO2\ mmHg$) for the last $60\ seconds$:

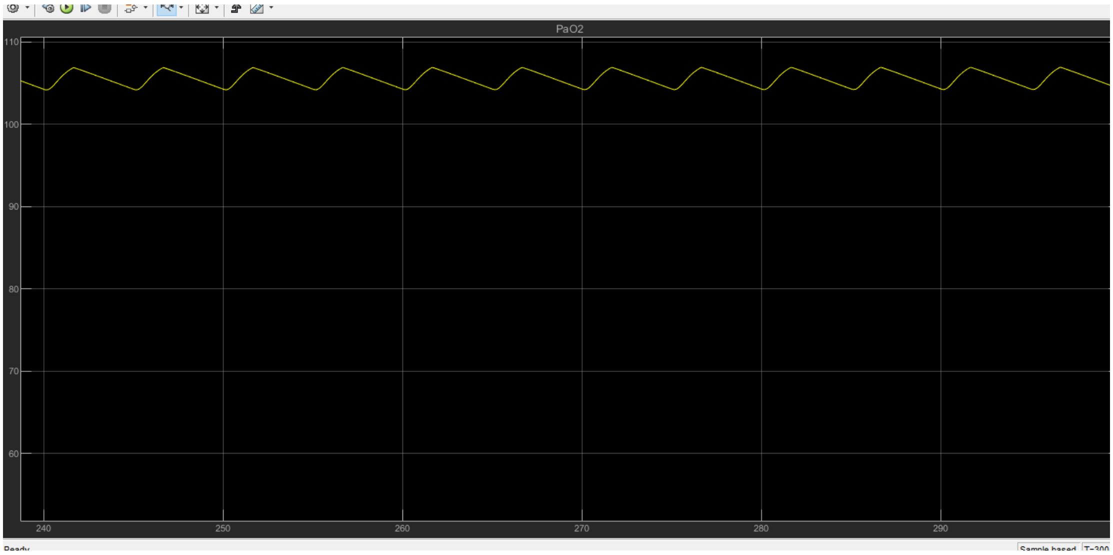

Figure B.2.7.

Partial pressure of the arterial carbon dioxide ($PaCO2 = PACO2\ mmHg$) for the last $60\ seconds$:

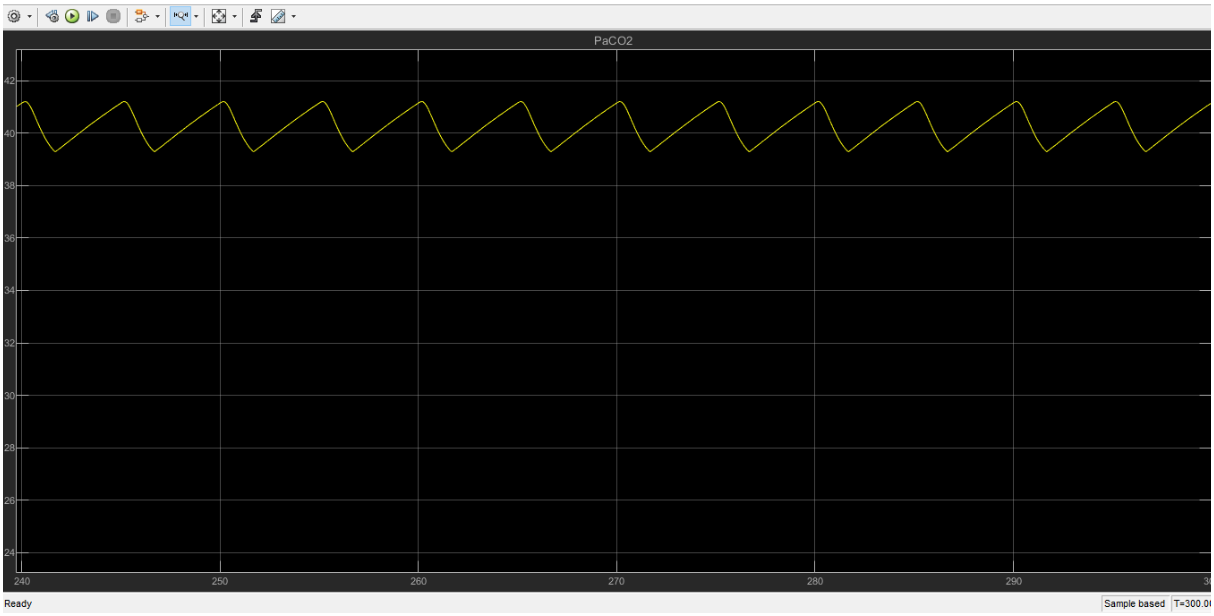

Figure B.2.8.

So, we obtained nearly; $PaCO2 = PACO2 = \ 41\ mmHg$ and $PaO2 = PAO2 = 104\ mmHg$ under the $C_{vO_2} = C_{vO_2 \iota c}$ and $C_{vCO_2} = C_{vCO_2 \iota c}$ and $Shunt\ = \ 0\ and\ F_p = 75ml\ (F_{ps} = 0, F_{ps} = 75)$ conditions.

Tissue Gas Exchange Model (3)

a. Realize the given tissue gas exchange model equations in Simulink. After including the tissue gas exchange model, perform the simulations once more during 5 minutes. Plot the arterial pressures of O_2 and CO_2 for the last 60 $seconds$. In addition, write down the final values of the oxygen and carbon dioxide concentrations in the arterial and venous blood.

Shunt value changed as parameter file, C_{vO_2} ve C_{vCO_2} values were calculated using the Tissue Gas Exchange Model with a constant selection of $F_p = 75\ ml$ for a and b.

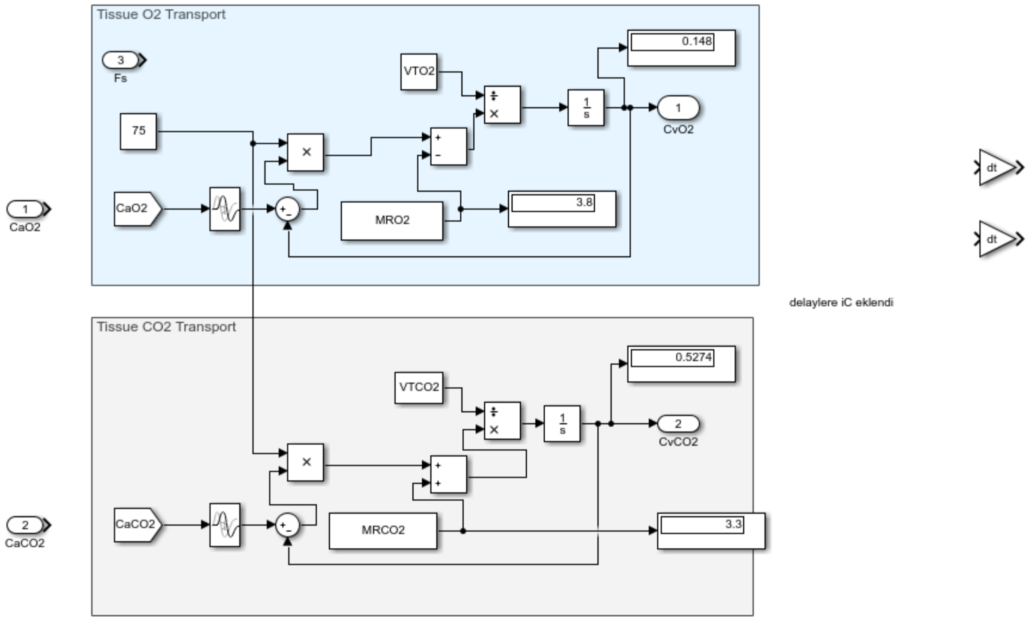

Figure B.3.1.

Under the these conditions, we obtain these pressures $(mmHg)$;

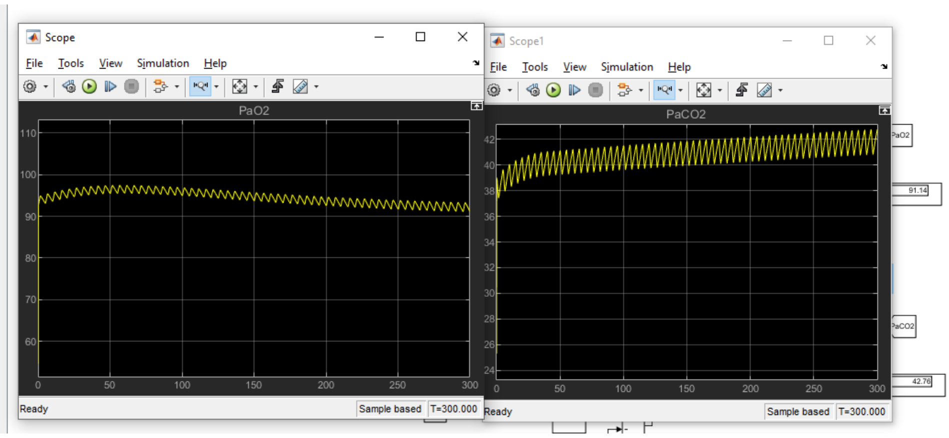

Figure B.3.2.

Partial pressure of the arterial oxygen ($PaO2\ mmHg$) for the last 60 $seconds$:

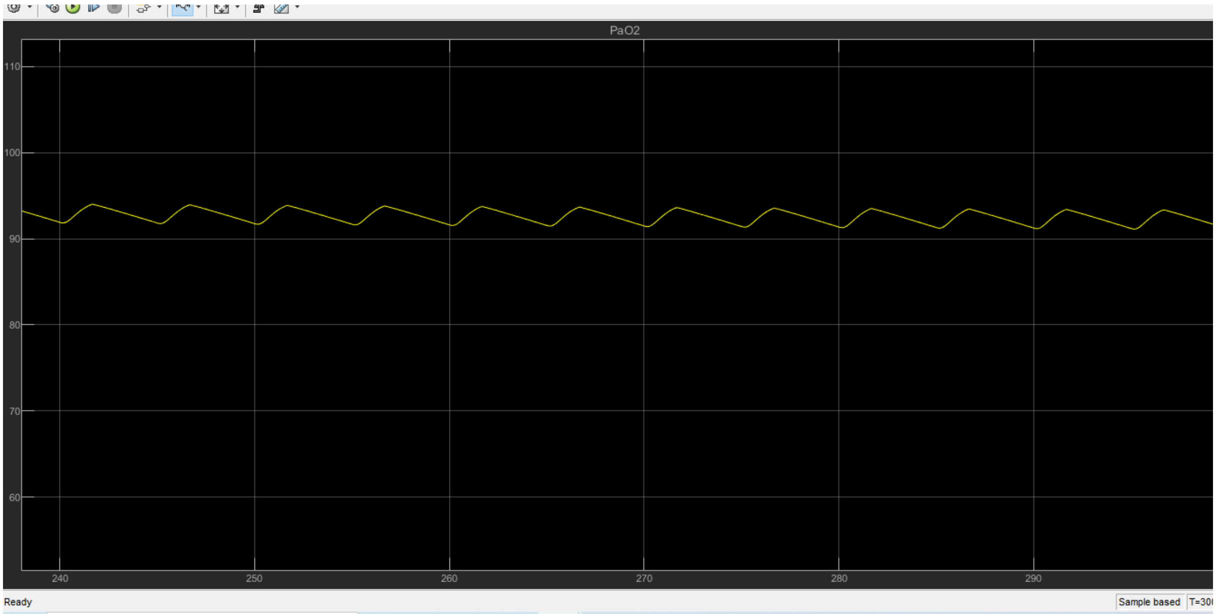

Figure B.3.3.

Partial pressure of the arterial $CO2$ ($PaCO2\ mmHg$) for the last 60 $seconds$:

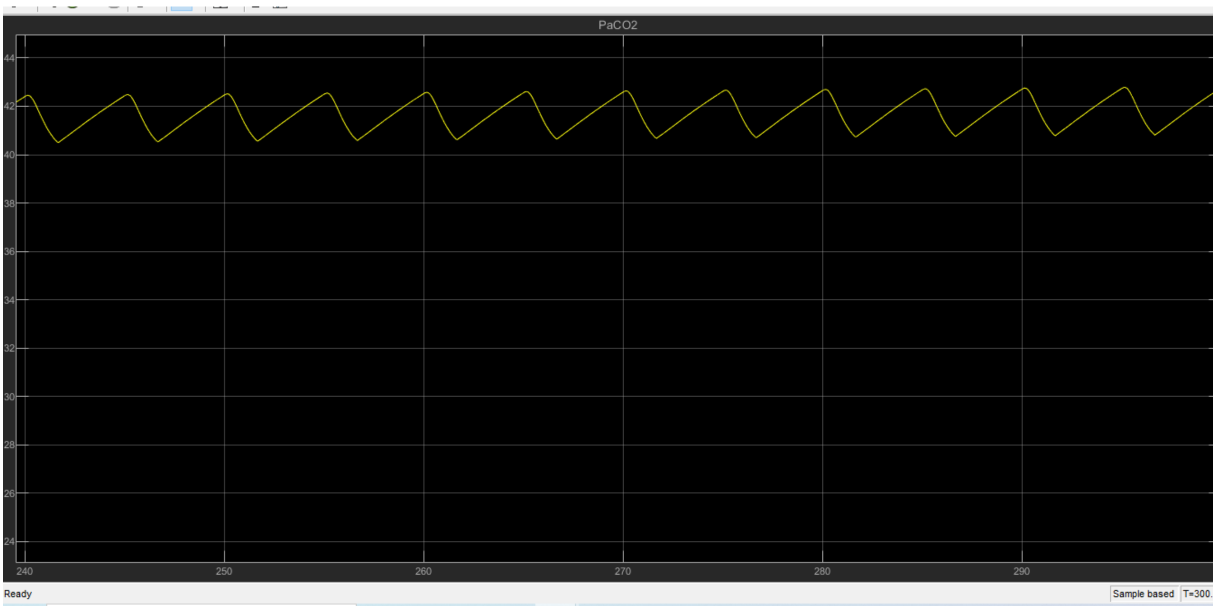

Figure B.3.4.

So, we obtained nearly; $PaCO2 = 42.7\ mmHg$ and $PaO2 = 91.14\ mmHg$ under the given condition for a part.

b. Increase the parameter MR_{O_2} by 50% and MR_{CO_2} by 100%. After that perform the simulations without changing any other parameters during 20 minutes. What happens to the arterial O2 and CO2 pressures? In reality, how does your body compensate these changes? Give your comments.

MR_{O_2} increased by %50 and MR_{CO_2} increased by %100 and simultaion 20 minutes:

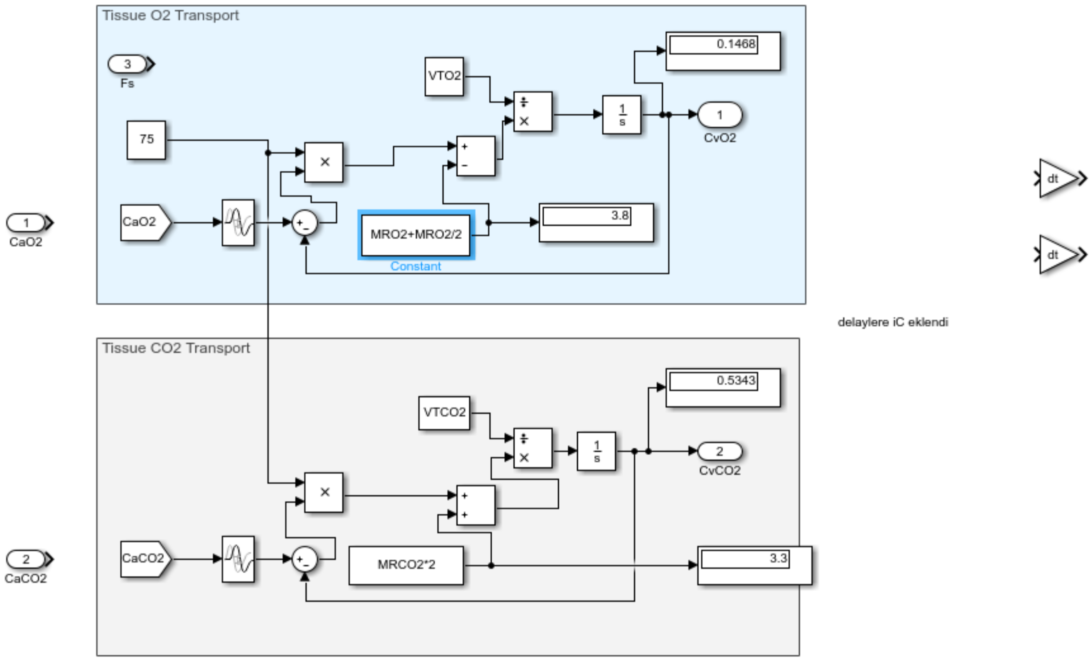

Figure B.3.5.

Simulation results for arterial $O2$ and $CO2$ pressures(mmHg);

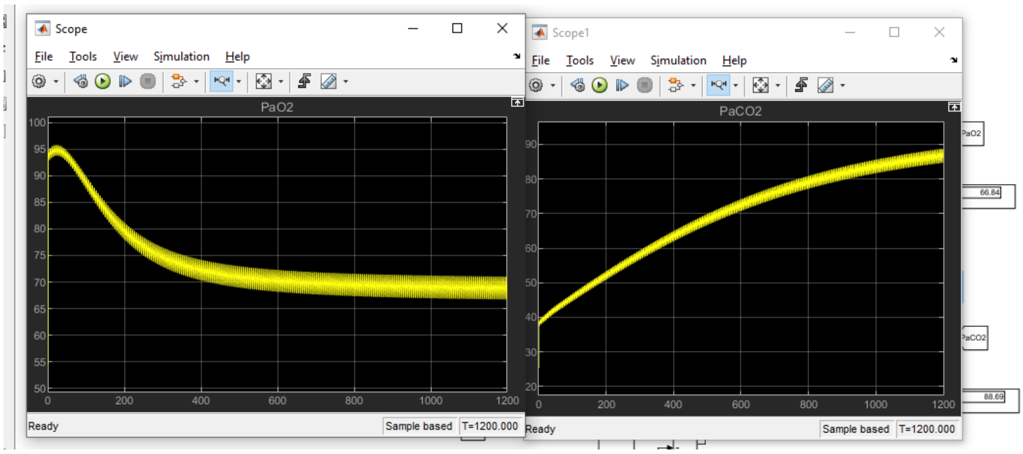

Figure B.3.6.

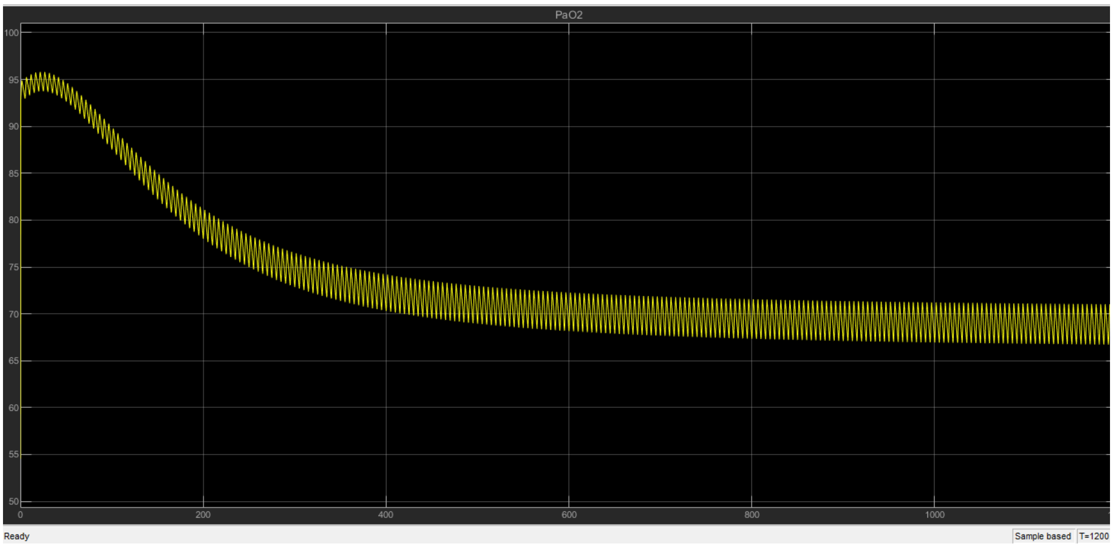

Figure B.3.7.

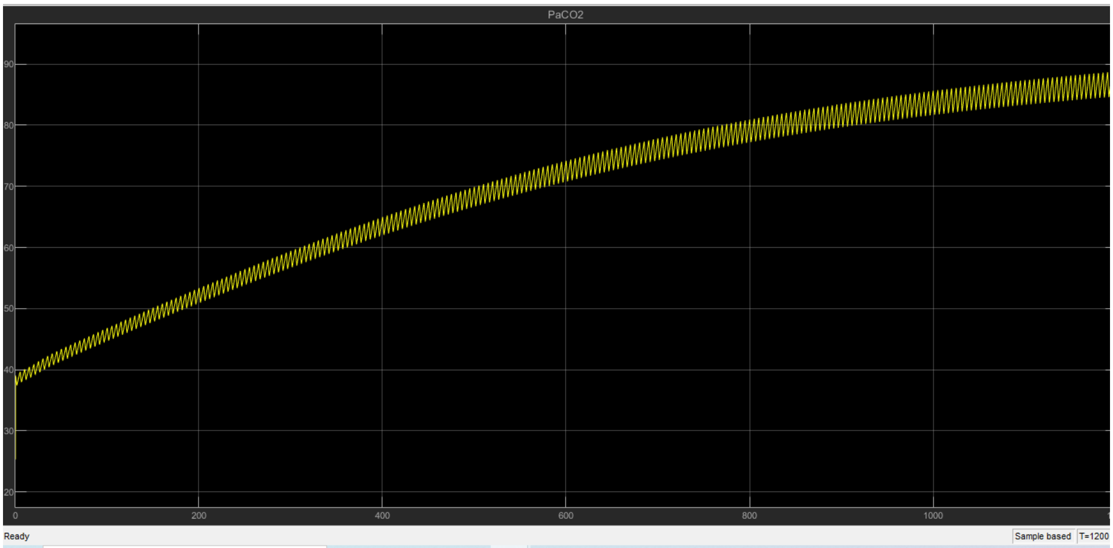

Figure B.3.8.

So, we obtained nearly; $PaCO2 = 88\ mmHg$ and $PaO2 = 66\ mmHg$ under the given condition for b part.

Since we use oxygen much more during exercise, it was expected that the oxygen in the blood would decrease and the carbon dioxide pressure would increase. **In real life, since the respiratory rate (RR) increase**s in line with the signals coming from the brain, that is, the ventilator system, a control mechanism ensures that the oxygen pressure does not fall below a certain level.

c. Now, it is time to connect the pulmonary system to the cardiovascular system you have modelled earlier. For this purpose, now take the blood flows ($F_s(t), F_{pp}(t)$ *and* $F_{ps}(t)$) from the cardiovascular system model (instead of using constant values). Run the simulation for 5 $minutes$ with nominal parameters given in parameter file and again plot the P_{aO_2} and P_{aCO_2} for the last 30 $seconds$.

$F_s(t), F_{pp}(t)$ *and* $F_{ps}(t)$ have taken from the cardiovascular system model

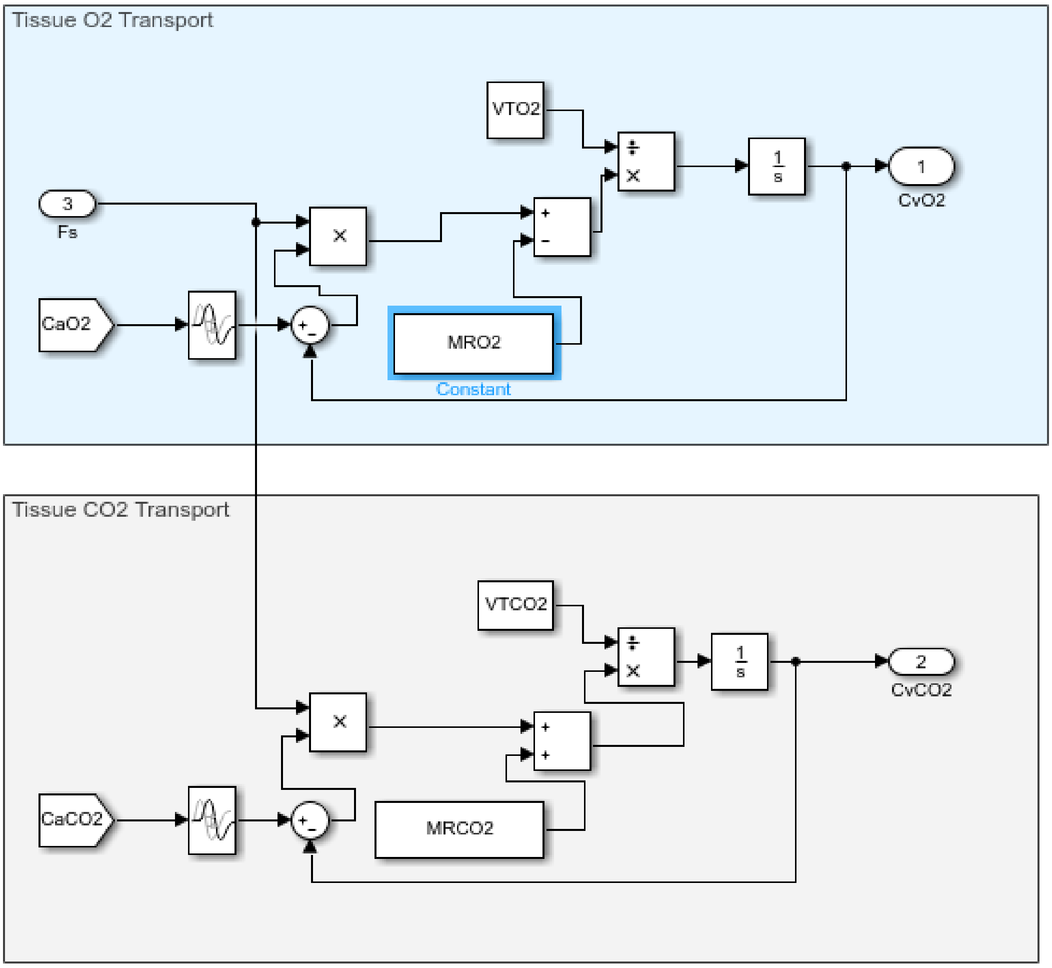

Figure B.3.9.

And we simulate 5 $minutes$. Results are given above;

Partial pressure of the arterial $O2$ and $CO2$ ($PaCO2\ mmHg$) for the last 60 $seconds$:

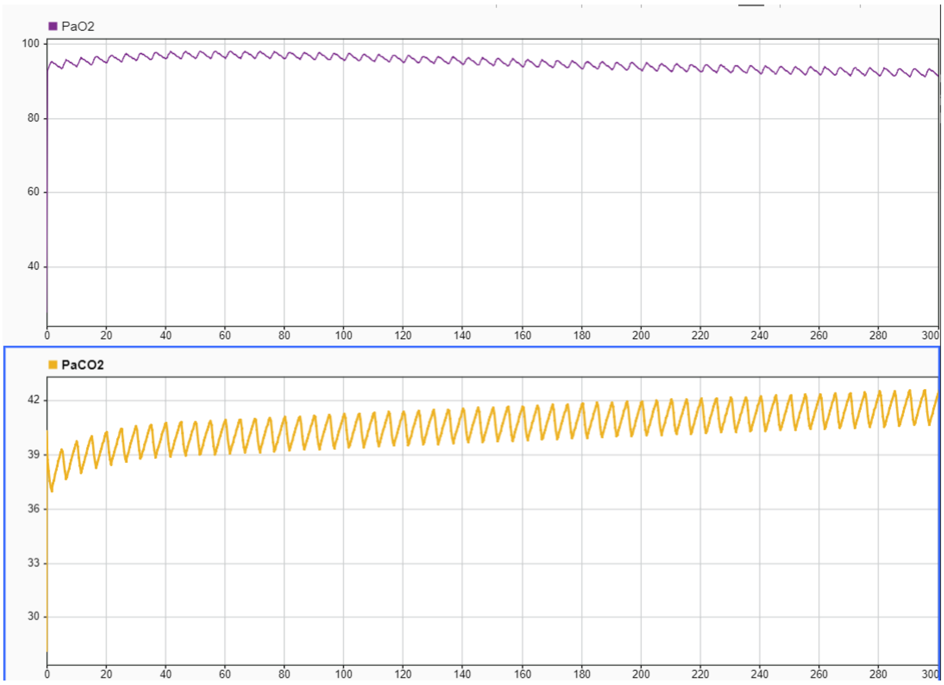

Figure B.3.10.

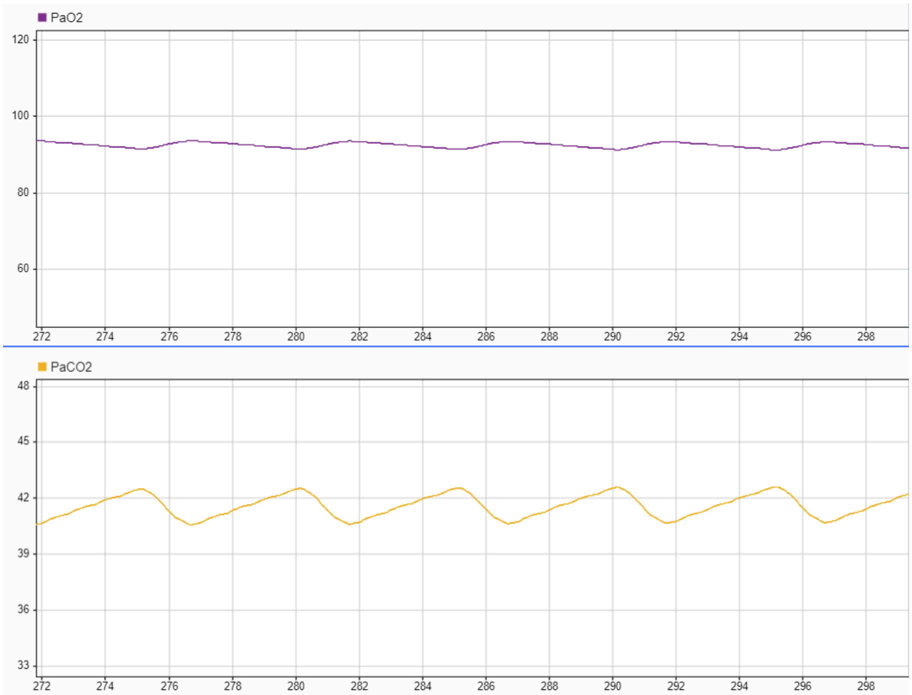

Figure B.3.11.

So, we obtained nearly; $PaCO2 = 41mmHg$ and $PaO2 = 92mmHg$ under the given condition for c part.

Ventilation Control System (4)

a. Instead of using constant P_{min} and RR, now calculate these inputs with the help of above equations. Run the simulations for 5 $minutes$ and plot the variation of RR and P_{min}. Also, plot the arterial $O2$ and $CO2$ pressures for the last 30 $seconds$.

For the calculated input values, the variations of RR and P_{min} for 5 $minutes$ are as follows:

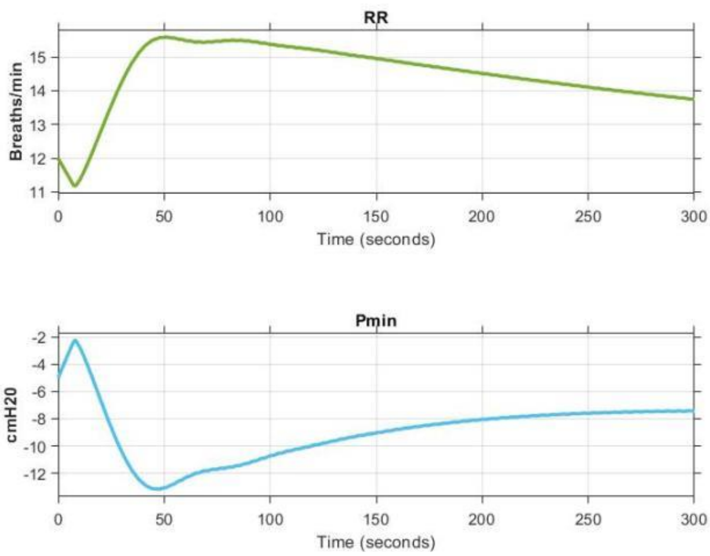

Figure B.4.1.

The arterial $O2$ and $CO2$ pressures for the last 30 $seconds$ of the simulation are as follows:

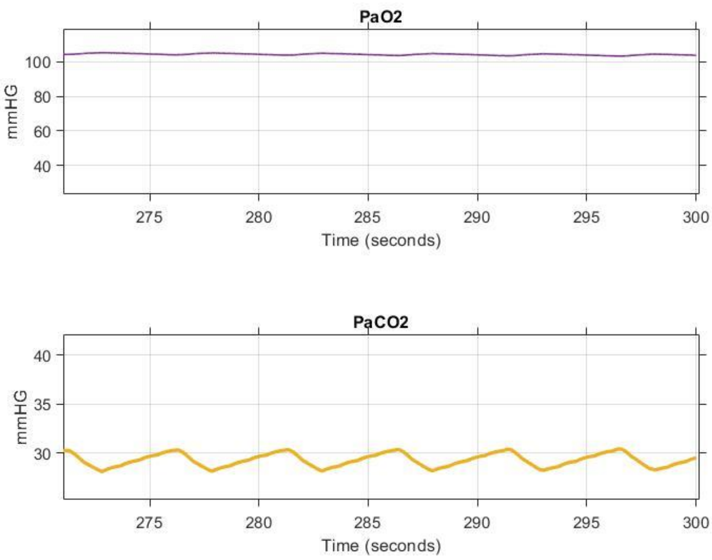

Figure B.4.2.

b. Similar to the question 3.b, increase the parameter MR_{O_2} by 50% and by 100% to simulate exercise condition. However, perform this change at $t = 240s$ and run the simulation for 10 minutes. Observe how the ventilation control center changes the respiratory rate and depth automatically. In addition, plot the variation of the arterial O2 and CO2 pressures during 10 minutes (whole simulation time). Comment on the results.

The SIMULINK scheme that will provide what is required is as follows:

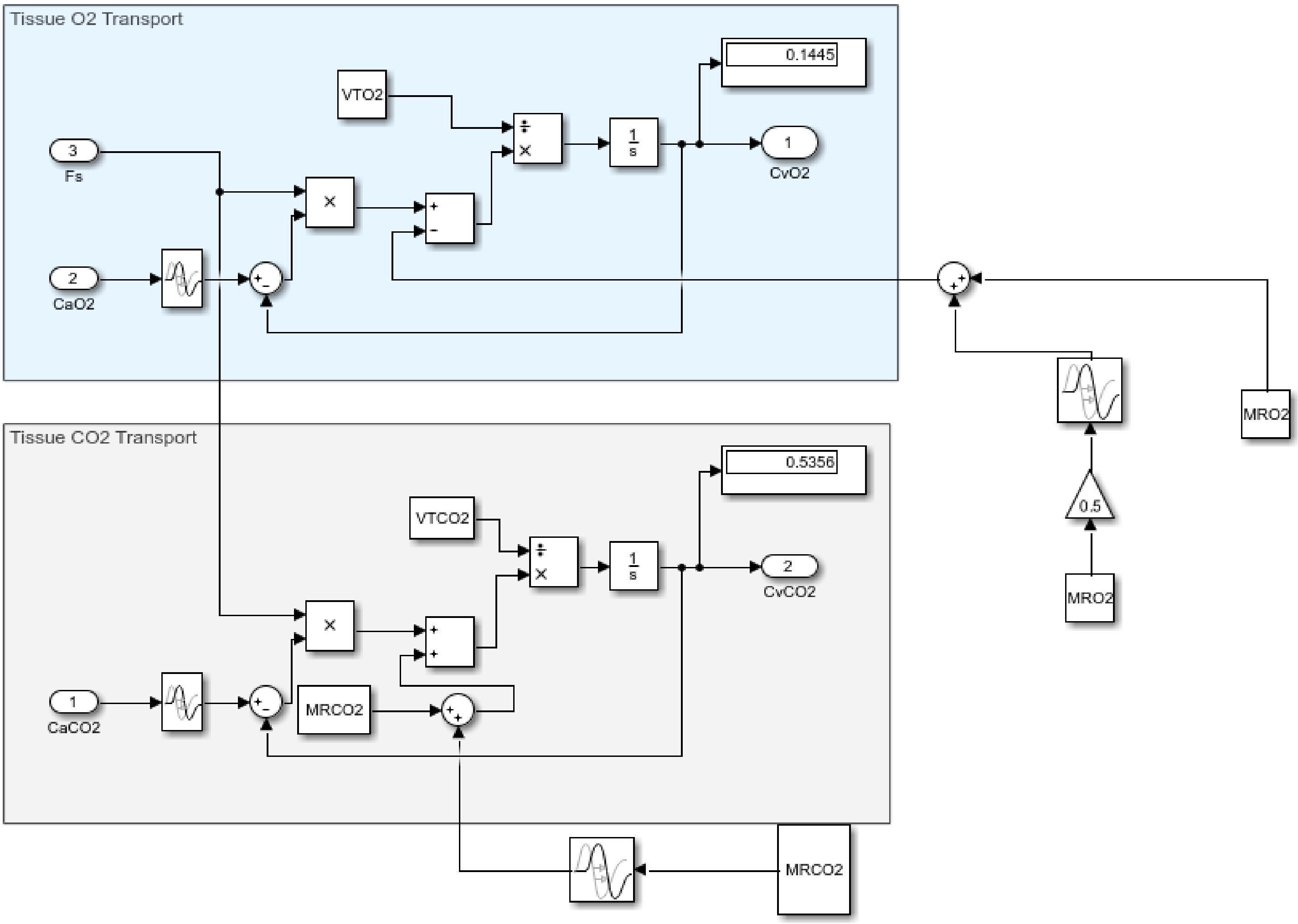

Figure B.4.3.

The change of respiratory rate and depth of the ventilation control center is as follows:

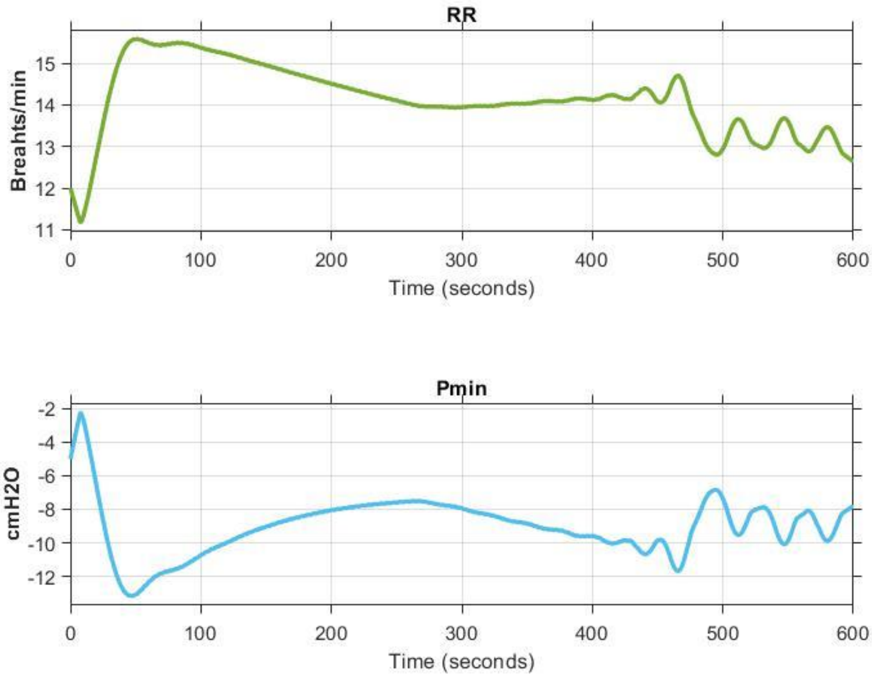

Figure B.4.4.

The arterial $O2$ and $CO2$ pressures for the $10 - minute$ simulation are as follows:

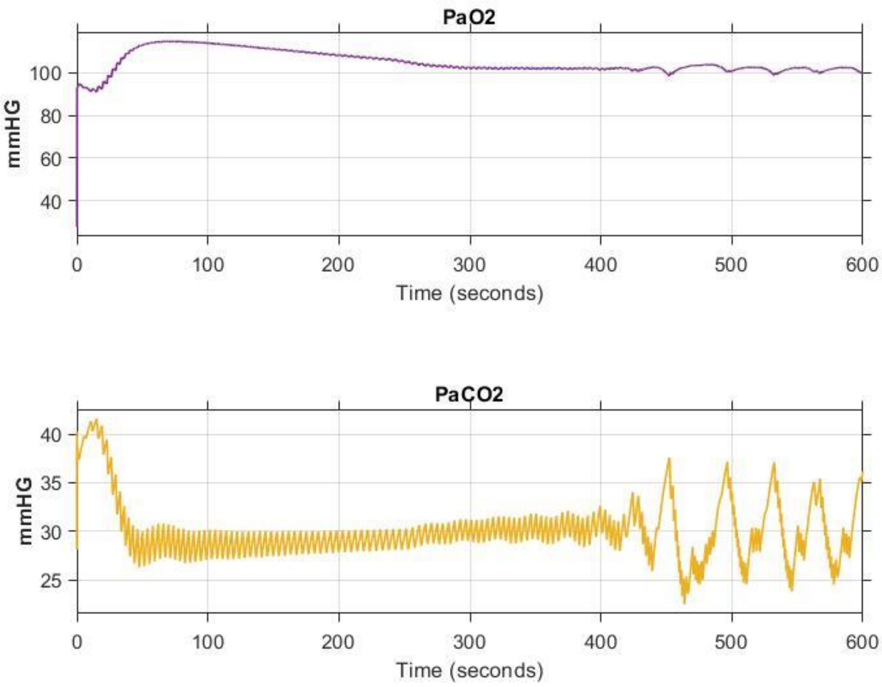

Figure B.4.5.

c. Comment on the term project.

We have seen that the brain works as a controller and acts like a feedback mechanism, balancing arterial $CO2$ and $O2$ pressures against any change (for example, exercises). It was a useful project that allowed us to better understand the brain's control structure. The part that we had difficulty with in the project was that the arterial $CO2$ pressure did not show up as we wanted in section b.3. We have seen that regardless of the type of a system being anything biological, chemical, etc., it can be controlled if the mathematical model is derived.

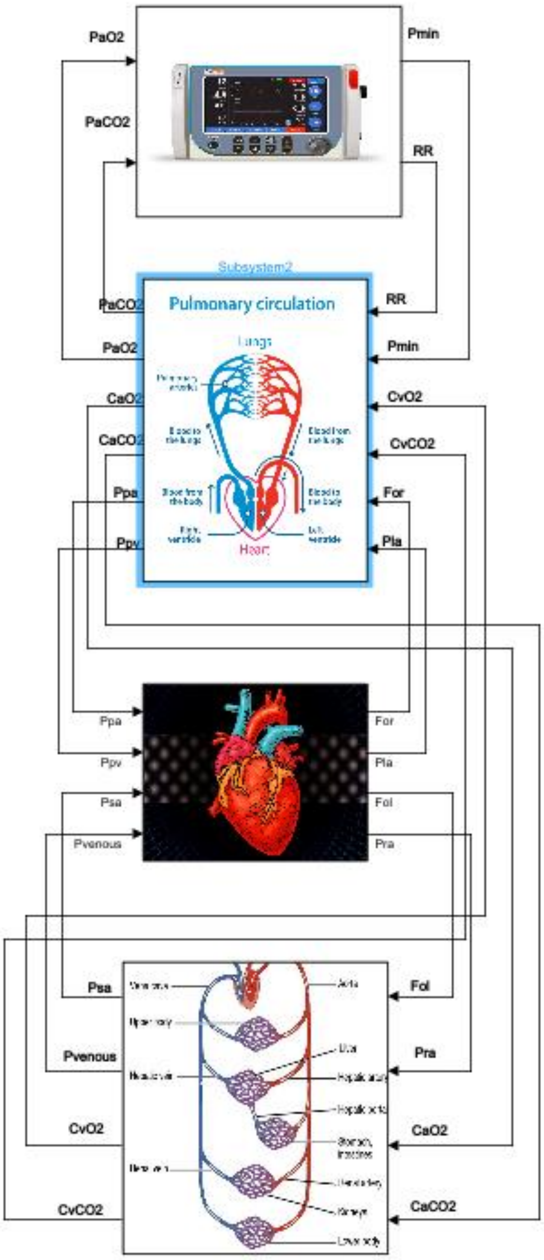

Figure B.4.6.