Modelling and design of a physical system to simulate the cardiovascular systemic arterial load using a windkessel model

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Outline

- Introduction
  - Objectives
  - Model Selection
- Parameter Identification
  - Methods
  - Results and Discussion
- Development of Physical System
  - Methods
  - Results and Discussion
- Conclusion

Introduction

- Cardiovascular diseases are one of the major causes of death all over the world [1]
- In such a case, it is very important to develop new and improved diagnostic and therapeutic methods and devices for the cardiovascular system.
- Modeling the cardiovascular system attempts to increase our understanding of its functions and processes.
- Due to complexity of system and data collection, modelling the complete distributed system is not feasible.
- CFD studies of the cardiovascular system is a powerful tool to aid in modelling of cardiovascular devices [2]
- But it requires proper boundary conditions
- So, to test the physical system, similar boundary condition/ load must be simulated
- Input impedance is a good choice of the boundary conditions and also to act as a load on the heart [2]

Goal

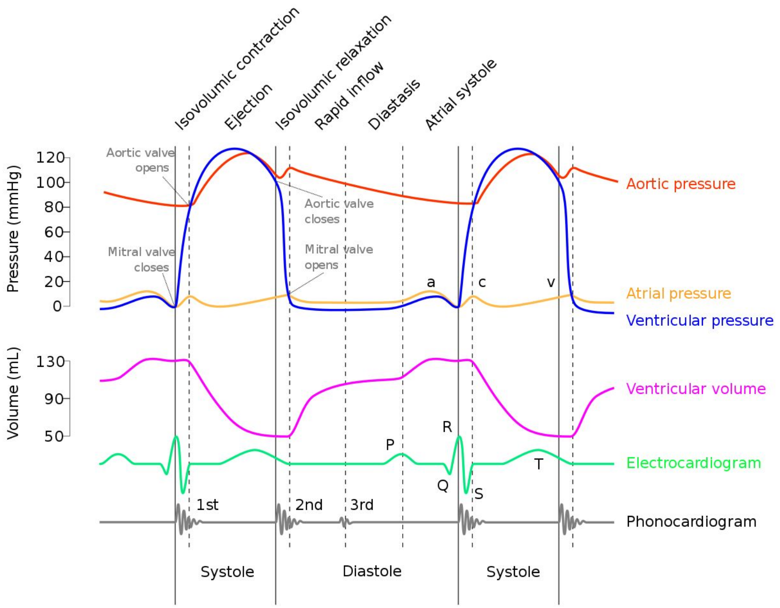
Design a physical module to simulate the input impedance of the systemic arterial circulation

Objectives

- Model selection
- Identification of parameters
- Convert the mathematical model into a physical model

Introduction

The Arterial Load



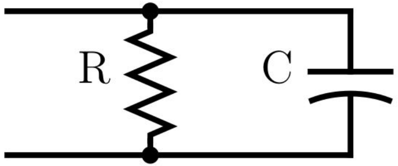
Cardiac cycle events -LV [Adapted under CC BY SA 4, WikiCommons]

- Initial clinical study used resistance as the arterial load
- Later, found the pulse pressure to be an indicator of cardiovascular morbidity
- So the impedance load must be able to:
    - Produce the mean flow properties
    - Produce the pulsatile characteristics

The Lumped Representation of Impedance

- 1773- Hales recorded that the behaviour of arterial load is similar to air-dome of Fire-engine- *Windkessel*
- High pulsatility of ventricular output vs the relatively constant aortic flow suggests presence of compliance element
- Frank (1889) suggested a model that contained - one resistance unit (Obey Poiseuille's Law) and one compliance unit.
- The pressure was assumed to be same at all points- Lumped model.

$$Q = \frac{P}{R} + C.\frac{dP}{dt}$$

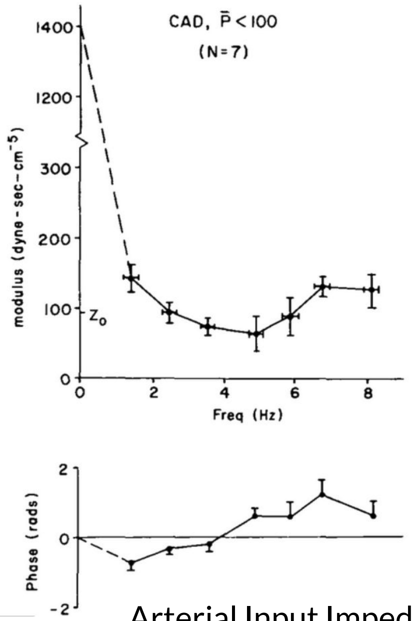


Two element Windkessel (WK)

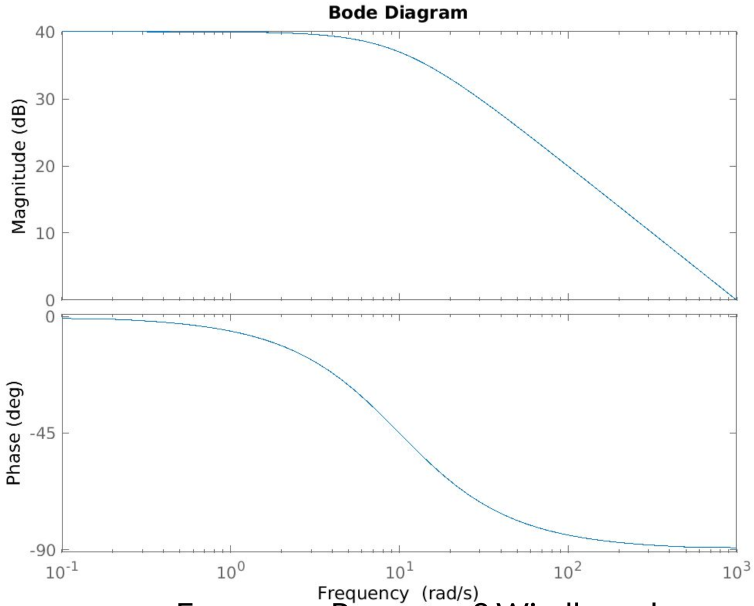
- It produces realistic physiological diastolic characteristics

Model Selection

Characteristic Impedance



Arterial Input Impedance [3]



Frequency Response 2 Windkessel

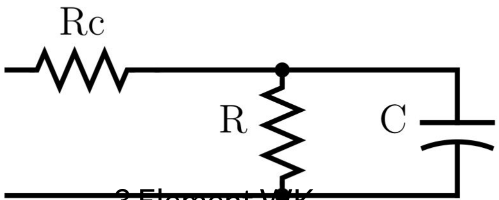
Model Selection

Characteristic Impedance

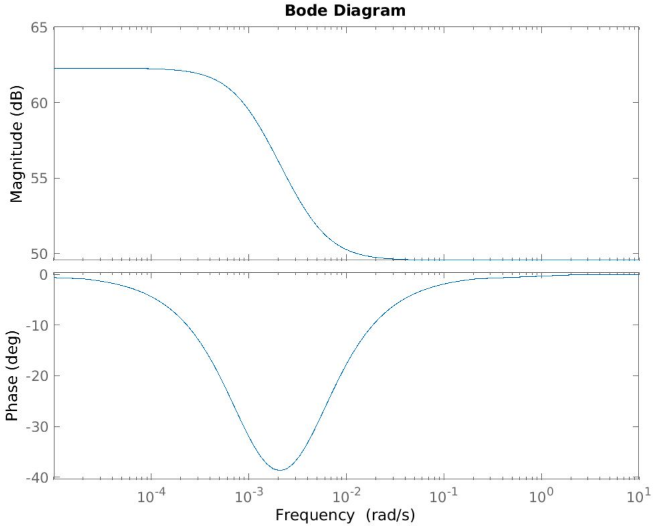
- Wave Propagation is not represented by a lumped model
- But the impedance saturates at characteristic impedance
- Wave reflection Coefficient:
- At high frequency, reflection wave is damped

$$\tau = \frac{Z_c - Z_{in}}{Z_c + Z_{in}}$$

- Introduce a new element - Characteristic 'Resistance'
-



3 Element WK

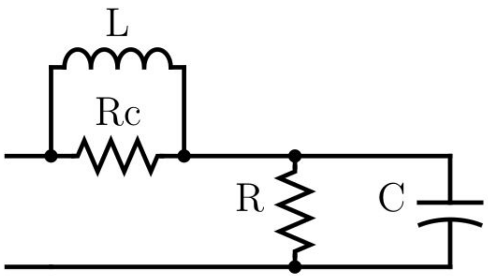


Frequency Response 3 WK

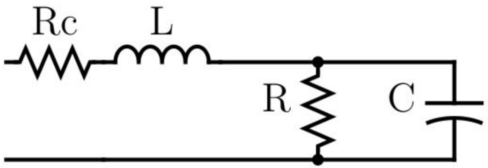
Model Selection

Inductance

- The introduction of new resistance introduces error at low frequencies [4]
- Low frequency motion should be influenced by inertia of blood [5]
- But inertia term is missing from the design
- So, introduce a inertia term -inductance



(a) WK4p Model

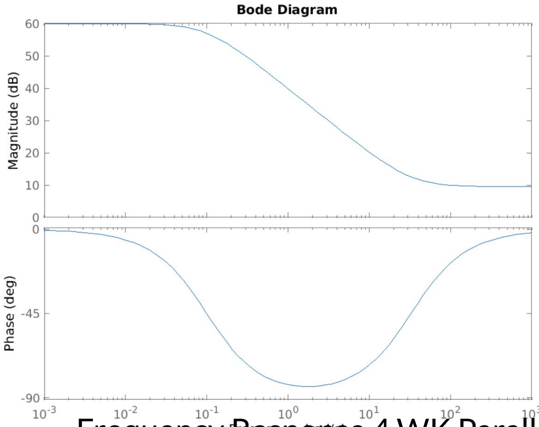


(b) WK4s Model

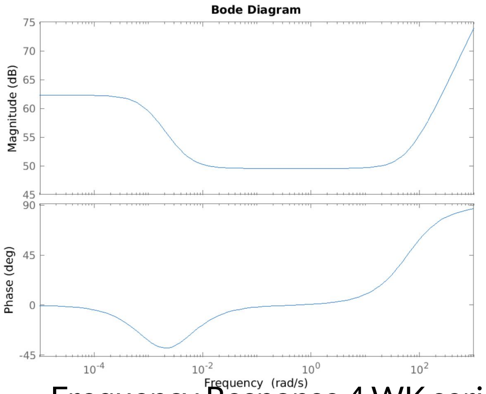
Model Selection

The Final Model Selection

- Both parallel and serial models have been used in previous research
- So, we need to make a choice between the two
- One study justified the use of parallel model using the similarity in the frequency response [5]
- But recently, it was found that the value of inductance in the series model could more closely explain the inertia of the blood [6]
- Moreover, we need the model to directly map to a corresponding hydraulic element
- So, we select the the series configuration



Frequency Response 4 WK Parallel



Frequency Response 4 WK series

Identification of Parameters

Introduction

- After selecting the model, we can use it to determine the required design parameters.
- The L,C, R and R_c were used as design parameters to be optimized (with necessary constraints)
- The parameter estimation can be done based on a measured signal in response to a certain input.
- We use aortic flow rate as input and aortic pressure as the measured signal.
- A Fourier analysis can be implemented to determine the impedance at different frequencies.
- The optimization was done using the Impedance Method.

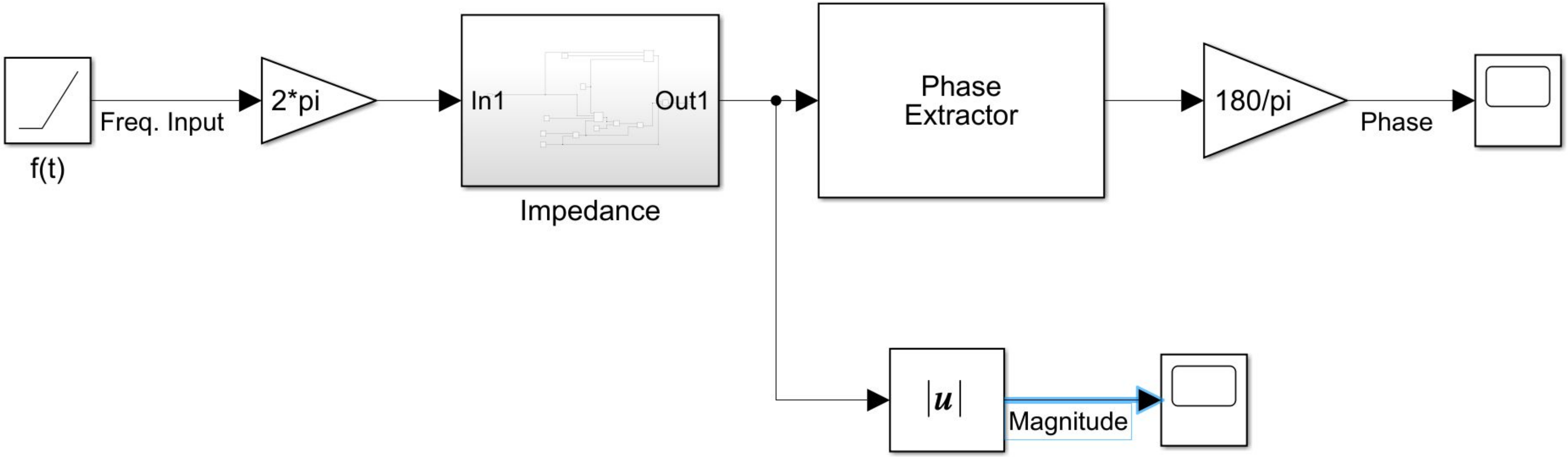
Identification of Parameters

Method

- The Parameter Estimation tool in Simulink Design Optimization™ toolbox is used to optimize the parameters values.
- We provided frequency as the input to the design tool and observed magnitude and phase of the impedance as the output.
- We use the nonlinear least square optimization method in the parameter estimation tool.
- After identifying parameters, we validated it with the reference data source.

$$time, t_i = (0, 1, 2, ..., 10)$$
$$\implies frequency, f(t_i) = (0, 2.54, ..., 25.4)$$
$$\implies impedance, Z = Z(f(t_i)))$$

Method



Impedance System in Simulink

Identification of Parameters

Method: Inputs

- The clinical data was obtained from the literature: 'Aortic input impedance in infants and children'. [We did not collect clinical data by ourselves] [7]

Age Yr.	Heart Rate beats/min.	Mean Pressure mmHg	Systolic Pressure mmHg	Diastolic Pressure mmHg	Mean FLow L/min
1.1	152.4	55.17	62.07	47.37	1.42

Frequency (Hz)	0	2.5	5	7.5	10	12.5	15	17.5	20	22.5	25
Magnitude	3125.9	448.66	340.7	492.55	450.52	906.79	574.12	456.4	570.8	546.01	434.76
Phase	0	225.71	5.64	23.14	33.82	26.5	27.56	14.03	16.24	34.98	25.55

Identification of Parameters

Method: Initial value Calculation

- The total peripheral resistance (TPR) can be determined from the 0 frequency impedance value. In case of WK4S, the TPR corresponds to Rc+R.
- At higher frequencies (2-8 Hz), the magnitude of impedance will remain close to Rc.
- The characteristic impedance can be estimated by using the averaged impedance magnitudes at higher harmonics.
- Compliance, C, can be estimated as the ratio of stroke volume to pulse pressure.
- The initial value inductance is approximated by taking in consideration the order of impedance values at higher harmonics.

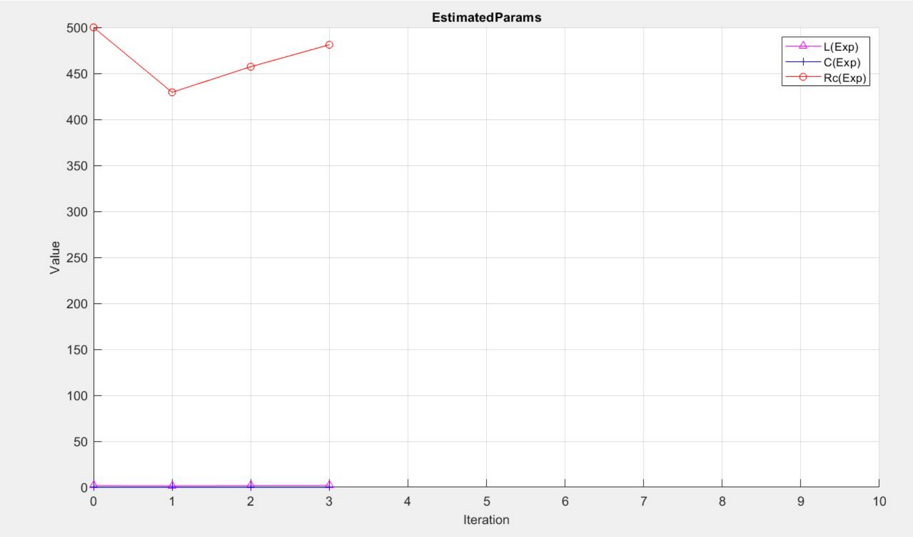
Identification of Parameters

Method: Initial Values of the Model

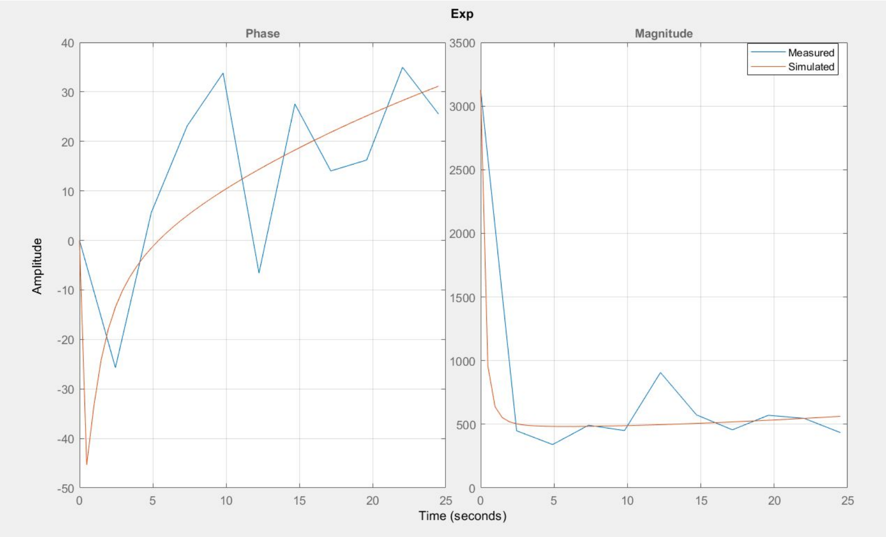
- $R + R_c = 3125.9$ dyn.s.cm^{-5}
- $R_c = 502$ dyn.s.cm^{-5}
- $C = 0.001$ cm^{5}/dyn
- $L = 1$ dyn.cm^{-5}.s^{2}

Identification of Parameters

Results:



Convergence of estimated Parameters



Optimized Fit

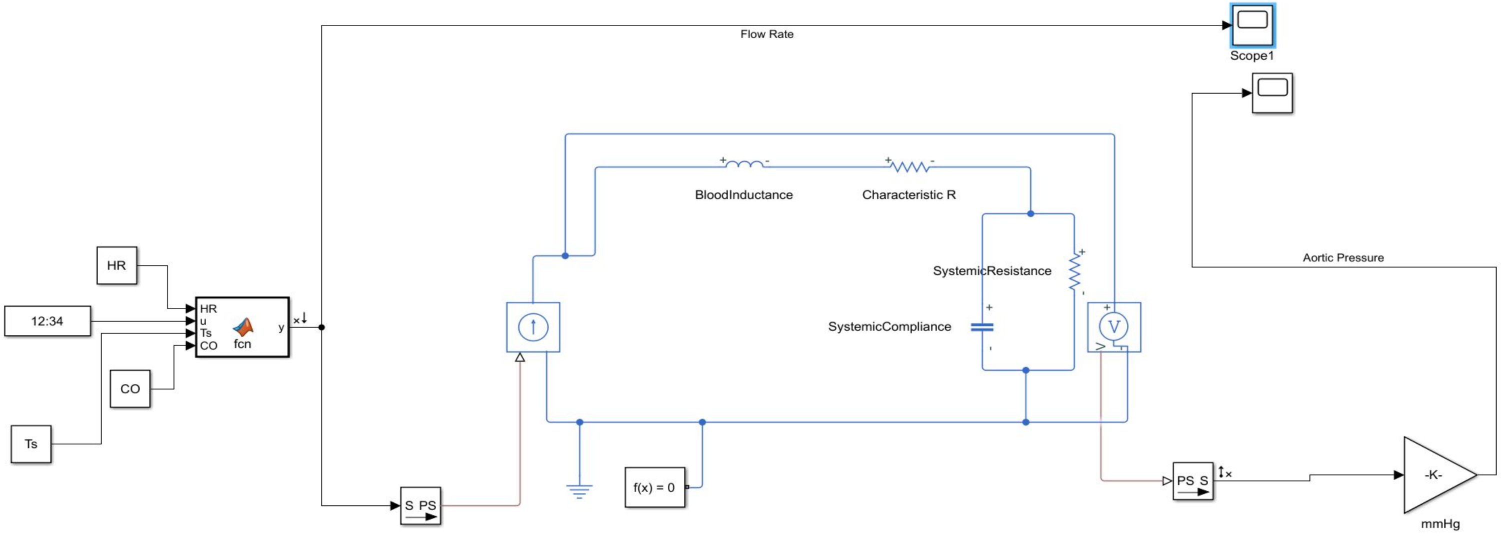
Identification of Parameters

Results: Optimized Parameters

Parameters	Optimized	Validation	Difference %
$R+R_c$ ($dyn.s.cm^{-5}$)	3125.9	3125.9	0
R_c ($dyn.s.cm^{-5}$)	481.75	480	0.36
C (cm^5/dyn)	4.23e-4	4.9e-4	13.6
L ($dyn.cm^{-5}.s^2$)	1.92	1.7	12.9

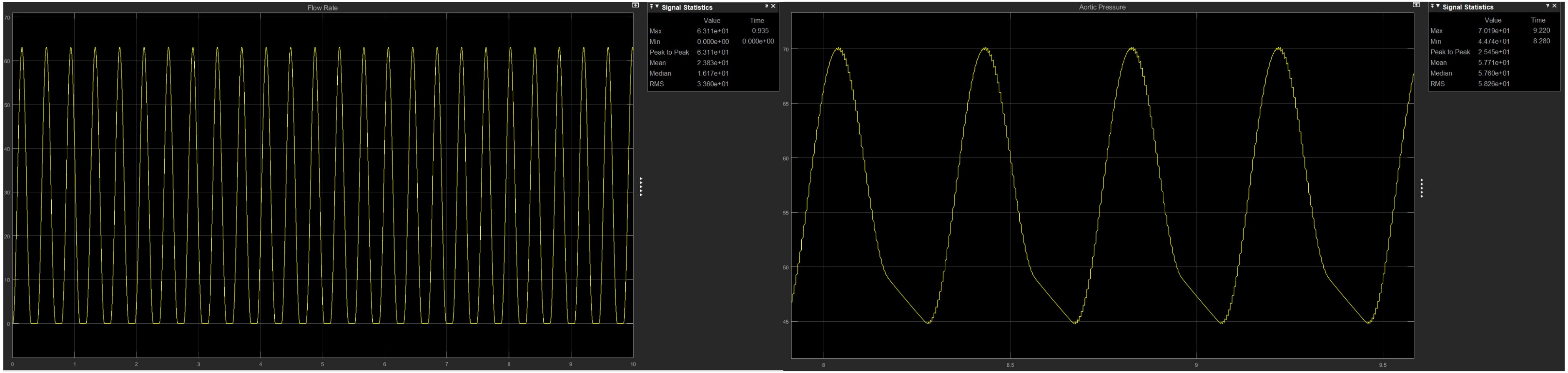
Identification of Parameters

Validation (Alternative)



The circuit representation of WK4s in Simscape

Validation (Alternative)



Input flow and Output AoP

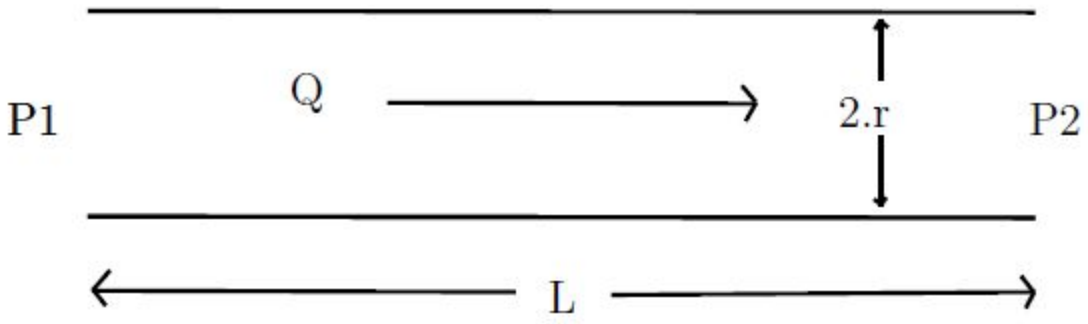
Introduction

- We use the parameters optimized before to build a physical model for the windkessel.
- We need to identify the corresponding elements in the hydraulic circuit.
- We consider a 40 % glycerol solution is considered to be the fluid due to its similar dynamic viscosity with blood.

Resistance

- When a fluid flows through a pipe, there is a drop in pressure across the any two points along the direction of the flow.
- Where,

$$R = \frac{\Delta P}{Q} = \frac{8\mu L}{\pi r^4}$$



Physical Model

Inductance

- The inductance represents the inertia of the fluid.
- It is a measure of the the force required to accelerate the blood.
- The inductance, L is described by:

$$\Delta P = L.\frac{dQ}{dt}$$

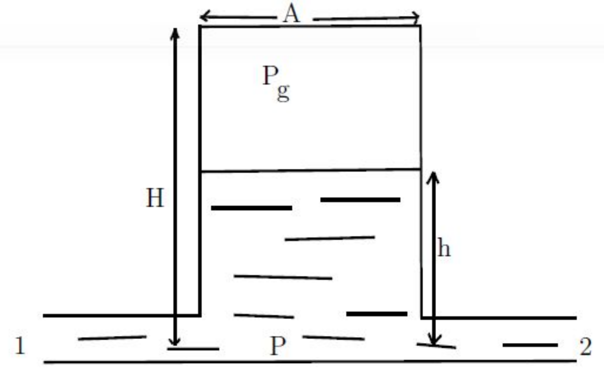
- For a conduit of cross-sectional area A and length l in which fluid of density ρ is flowing, the inductance will be:

$$L = \frac{\rho . l}{A}$$

Compliance

- Compliance in its literal sense means change in volume due to applied load or pressure.
- For a system shown, compliance can be represented as,

$$C = \frac{V}{P_g} = \frac{A.(H-h)}{P_g} = \frac{A.(H-h)}{P-\rho.g.h}$$



Methods

- To achieve the flow rate through a given cross sectional area pipe, Kung et al. [1] showed that parallel resistors can be used to create the resistance required.
- Kung showed that a nearly constant resistance can be built using capillary tubes packed in a cylinder. It also ensures ensures that the flow is laminar which is necessary to apply Poiseuille's Law.
- The total Resistance of the system is given by :

$$Total Resistance, R_{total} = \frac{8\mu l}{N\pi r^4} = \frac{8\mu l}{A.r^2}$$

Where, N is the number of capillary tubes and r is the inner radius of the capillary tubes

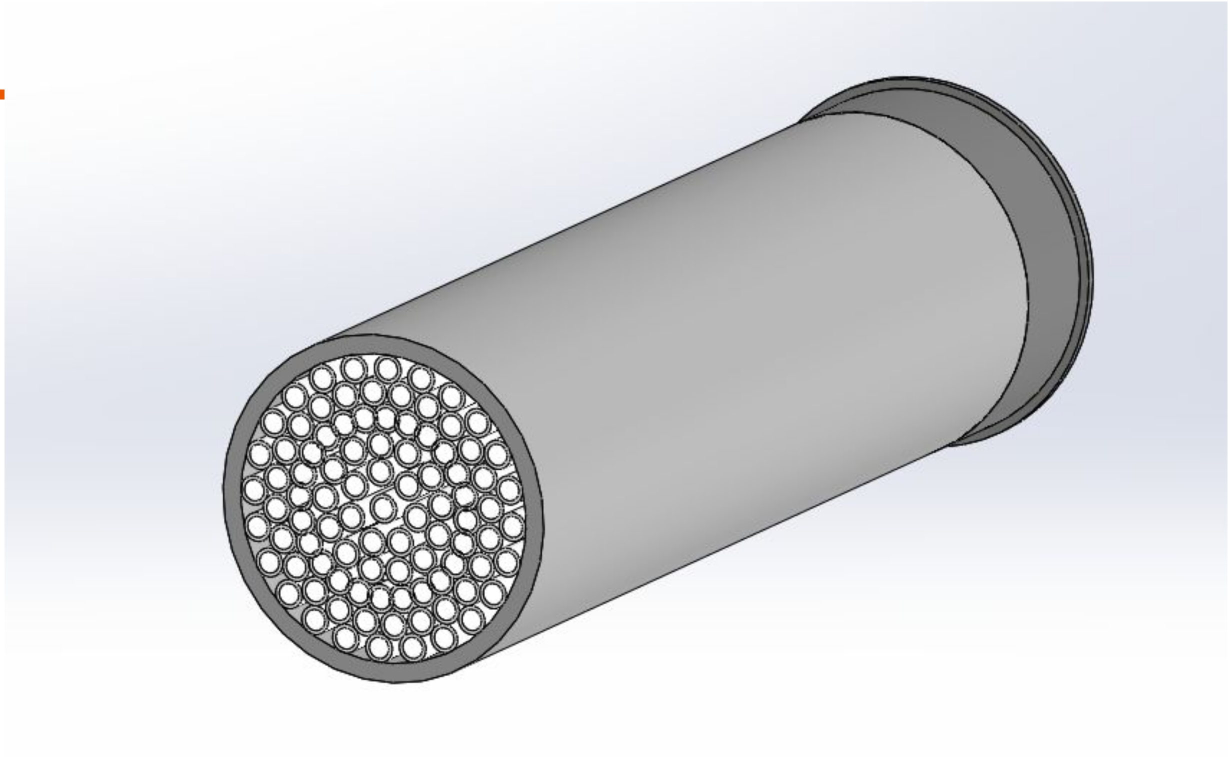
Methods

- We want to introduce inductance in the model
- The Compliance, due to its large cross section would have low inductance
- So, the inductance of the downstream components can be ignored
- We assign the inductance to the characteristic resistance, Rc module

$$R_{total} = \frac{8\mu L}{\rho r^2}$$

- For the compliance chamber, height is calculated for a compliance value and mean fluid pressure
- The air pressure is then adjusted to maintain the pressure of liquid in the circuit.

Physical Model



Capillary tube packed resistance module

Results

- By following the methods, we get the following dimensions for the setup.

- For the characteristic resistance, Rc with inductance, L incorporated in it:
  - Inner radius of capillary tubes: 0.31 mm
  - Length of capillary tubes: 10 cm (standard length)
  - Number of capillary tubes: 1882
  - Radius (inner) of the cylinder of pack the capillary tubes: 23.2 mm (assuming capillary OD=1mm)

Results

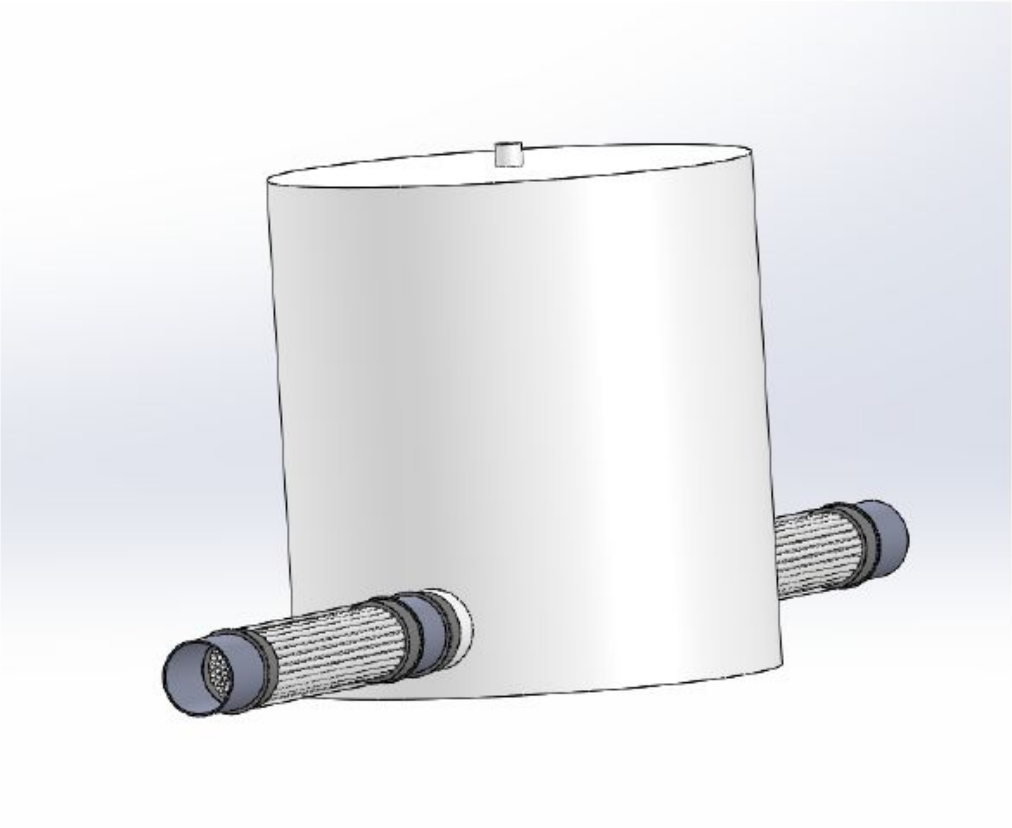
- For the other resistance, R module:
  - Inner radius of capillary tubes: 0.24 mm
  - Length of capillary tubes: 10 cm (standard length)
  - Number of capillary tubes: 1000
  - Radius (inner) of the cylinder of pack the capillary tubes: 17mm (assuming capillary OD=1mm)

Physical Model

Results

- For the compliance, C module:
  - Inner radius of the cylindrical chamber: 10 cm
  - Height of the liquid column: 11.5 cm [Will change with mean pressure]
  - Total height of the cylinder: 25 cm
  - Pressure of air above the liquid: 60800 dyn.cm^{-2} [Will change with change in mean pressure]

Physical Model



CAD representation of assembled system

Physical Model

Discussion

- Introduction of inductance in Rc increases its diameter
- Pumps may not be compatible with large diameter
- The diameter can be adjusted by using a non-standard shorter capillary tubes.
- Reduction in diameter will also reduce the sectional area of the other conduits and will add extra inductance to the circuit
- A conduit of gradually increasing diameter may be used
- The area of the compliance should always be large enough for assumptions to hold
- Laminar flow should be ensured for maximum flow rate in the circuit

Conclusion

- We have used the modelling techniques to design a device that can act as the systemic arterial load.
- The device, when fabricated can be used to test artificial valves or ventricular-assist devices.
- The optimization analysis on the electrical model was used to finally design the mechanical (hydraulic) system.
- We have been able to incorporate the inductance in the design.
- Use of modelling tools like Simulink made the process easy and fast
- We have used a single windkessel unit to model the systemic circulation only.
- Similar approach can be used to model and design a system for the pulmonary circulation and cascaded windkessel models

References (For presentation only)

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