Nonlinear Control of a Hybrid Pneumo-Hydraulic Mock Circuit of the Cardiovascular System

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Abstract

Objective: Hybrid cardiovascular mock circuits (HMC), designed for dynamic testing of Ventricular Assist Devices (VAD), offer physiologic accuracy by sequestering model complexity *in silico* and ease of construction by reducing number of model elements *in vitro*. Despite superior response time and precision, pneumatic actuation is avoided in HMCs due to nonlinear dynamics and noise. We tested the hypothesis that a HMC consisting of a variable elastance-driven numerical circuit coupled to a pneumo-hydraulic physical circuit can be controlled without linearizing system dynamics. *Methods:* Reference left ventricular and aortic pressures generated *in* silico were tracked, respectively, in *in vitro* preload and afterload reservoirs by controlling non-linear pneumatic dynamics using the Lyapunov stability criterion. A centrifugal pump, the speed (i.e. flow) of which was adjusted using PID control, was interposed between the reservoirs and mimicked the VAD under evaluation. The flow of a recirculating gear pump was controlled by the backstepping method to equalize reservoir fluid volumes by rejecting pressure and flow disturbances. Sensor noise was reduced with discrete-time Kalman filtering. *Results:* Our results showed that normal, failing and assisted cardiovascular physiologies were numerically simulated and tracked at physical VAD terminals with high accuracy. Reservoir volumes remained stable at various combinations of heart rate, pressure, and VAD flow. *Conclusion:* The HMC described here offers a stable performance testing platform for VAD prototypes. *Significance :* This is the first proof that hybrid systems using pneumatic actuation at hydraulic interfaces can optimally be regulated with nonlinear controllers to achieve precise reference tracking and robust disturbance rejection.

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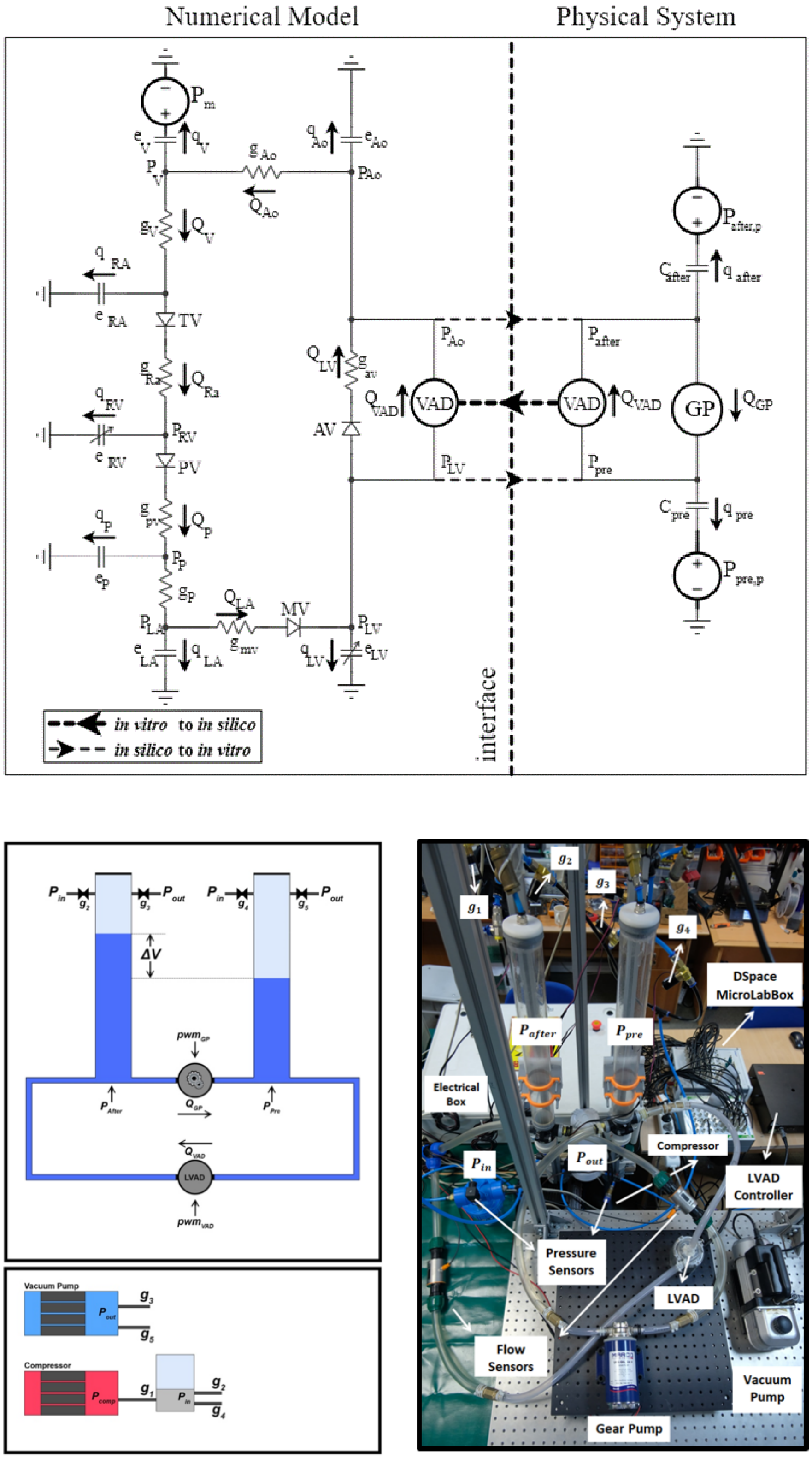
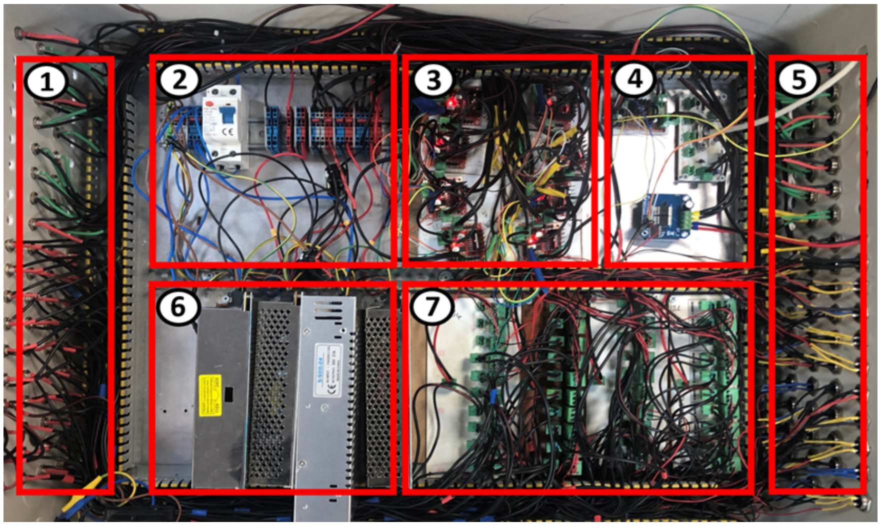

Numerical Model
Physical System
interface
in vitro to in silico
in silico to in vitro
TV
PV
AV
MV
VAD
GP
Electrical Box
DSpace MicroLabBox
Compressor
LVAD Controller
Pressure Sensors
LVAD
Flow Sensors
Vacuum Pump
Gear Pump
Vacuum Pump
Compressor

Figure 2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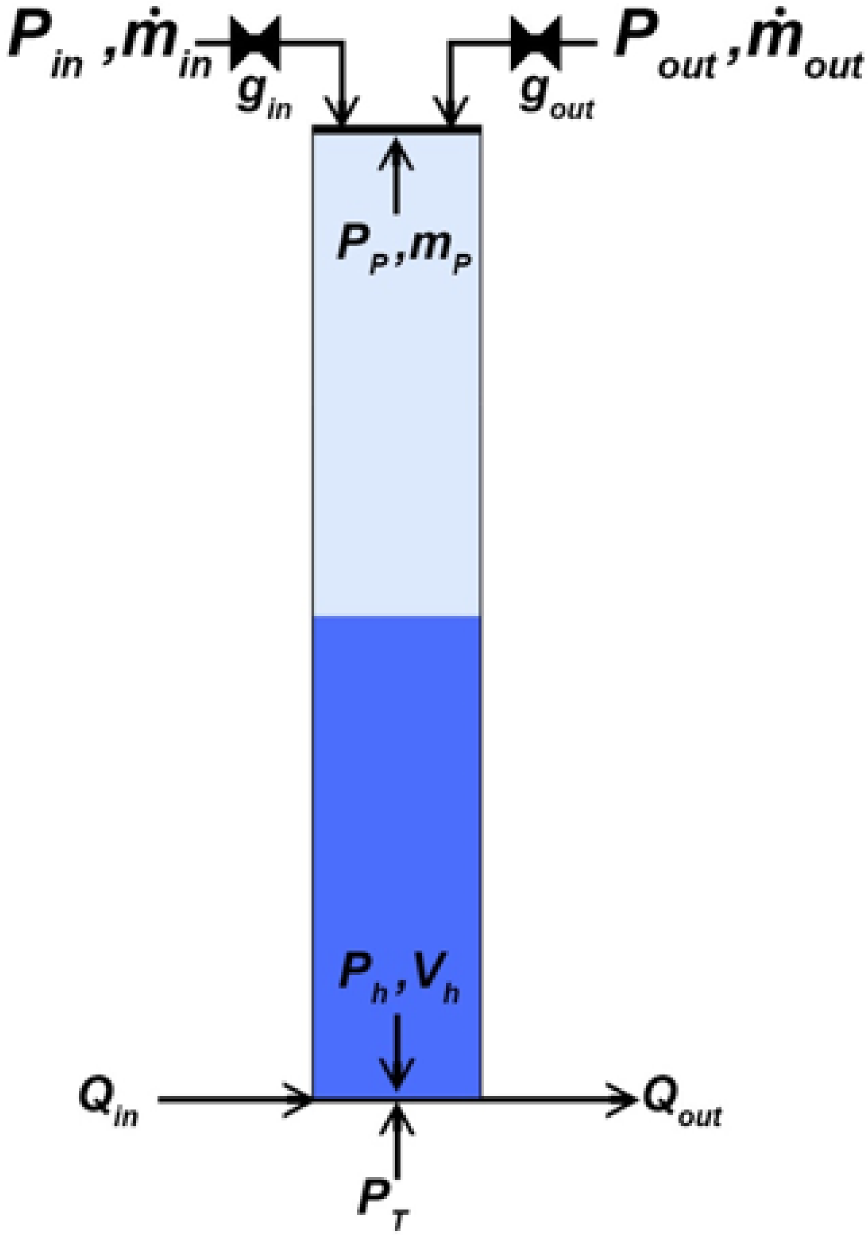
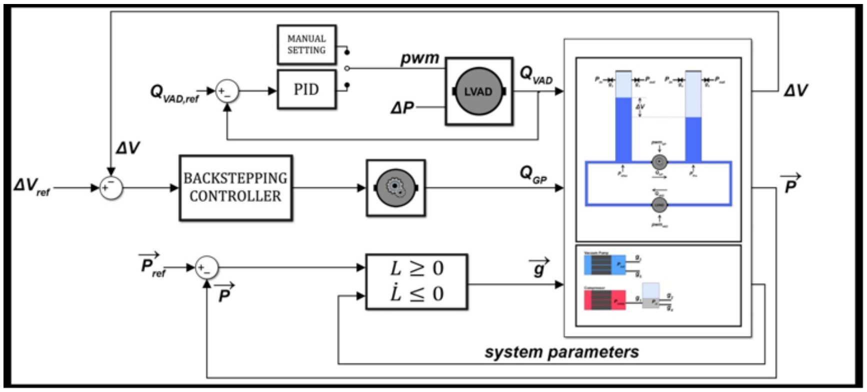
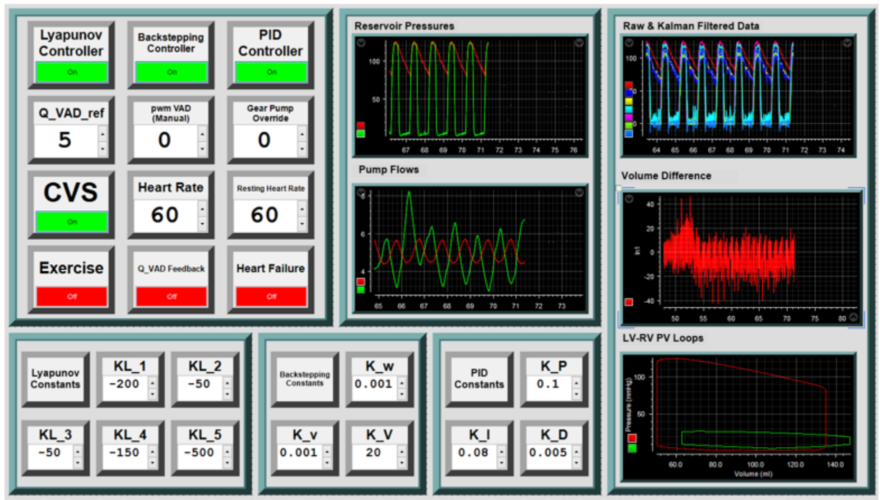
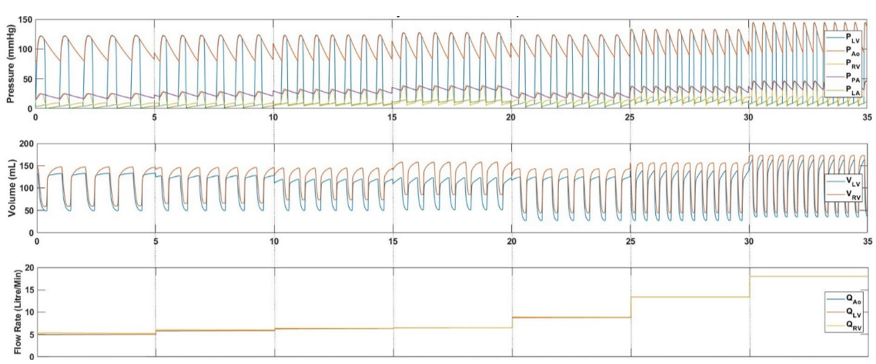
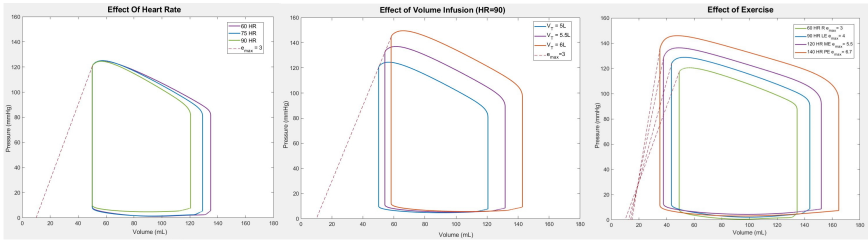

P_{in} ,$\dot{m}_{in}$
g_{in}
g_{out}
P_{out},$\dot{m}_{out}$
P_P,m_P
P_h,V_h
Q_{in}
Q_{out}
P_T

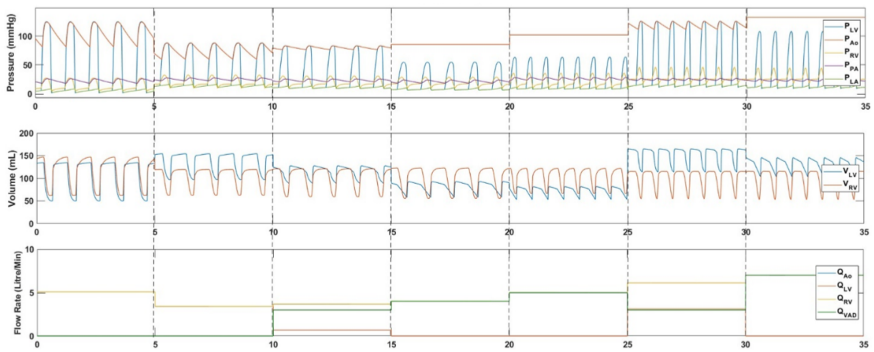




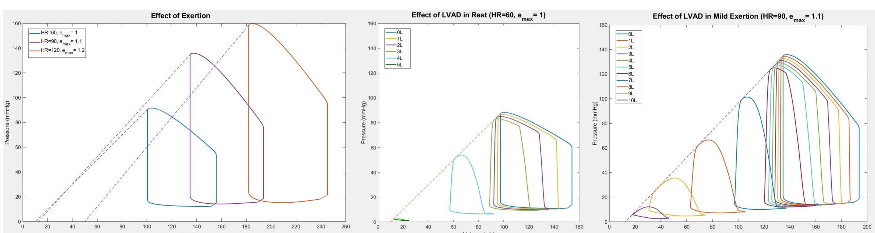


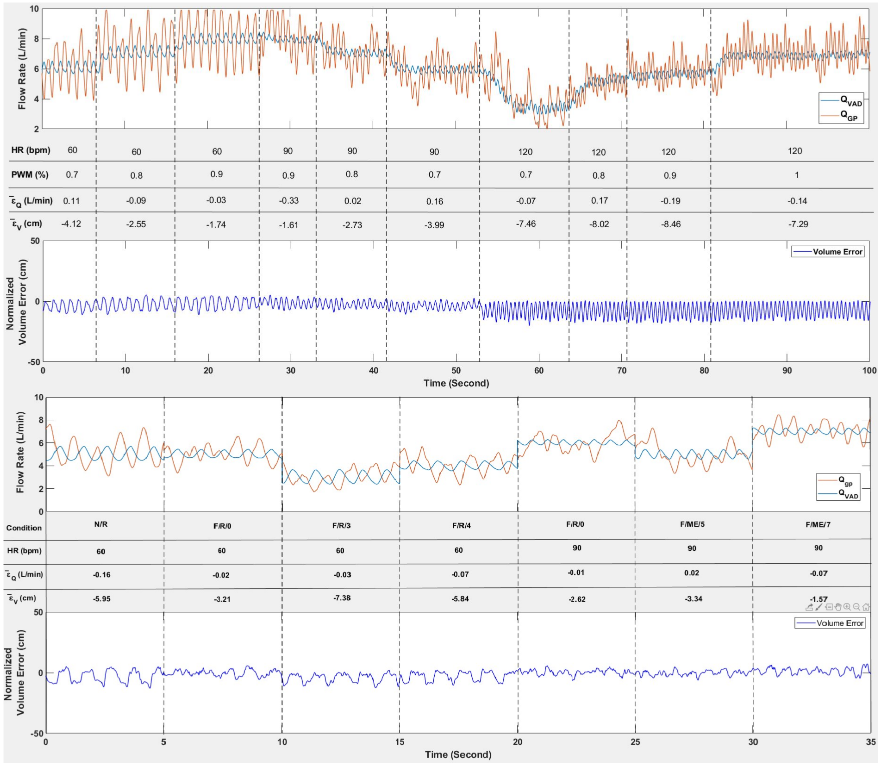
Cond	N/R	N/R	N/R	N/R/V	N/LE	N/ME	N/PE
HR	60	75	90	90	90	120	140
SV	83	77	79	72	98	112	128
CO	5.0	5.8	6.3	6.5	8.8	13.4	18.0
MAP	93	93	94	98	98	103	110
SW	7747	7187	7452	7032	9637	11573	14123
EF	63	61	66	59	78	81	79

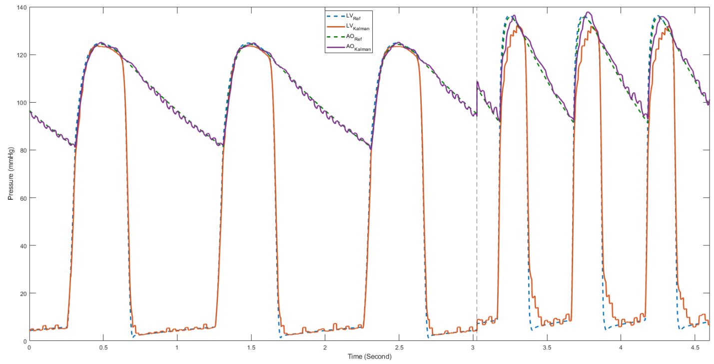




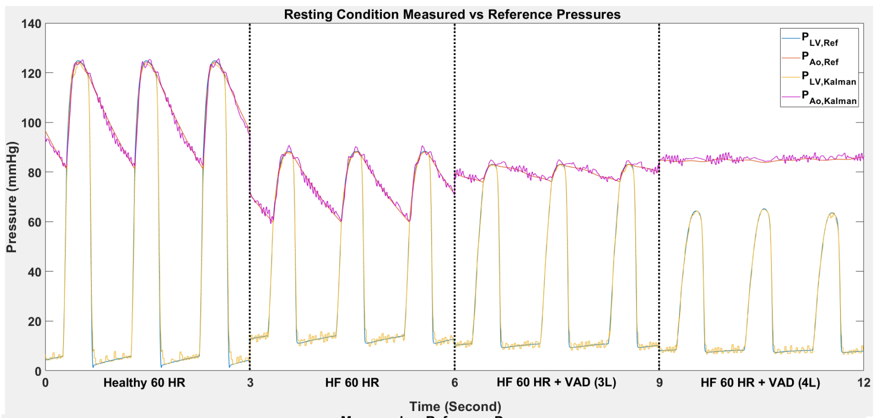
Cond	N/R	F/R/0	F/R/3	F/R/4	F/R/5	F/ME/5	F/ME/7
HR	60	60	60	60	90	90	90
SV	84	57	39	N/A	N/A	51	N/A
CO	5.0	3.4	3	N/A	N/A	1.1	N/A
Q_{AO}	5	3.4	3.6	4	5	6.1	7
MAP	95	68	78	85	102	115	132
SW	8008	3895	3042	N/A	N/A	5882	N/A
EF	63	37	31	N/A	N/A	31	N/A



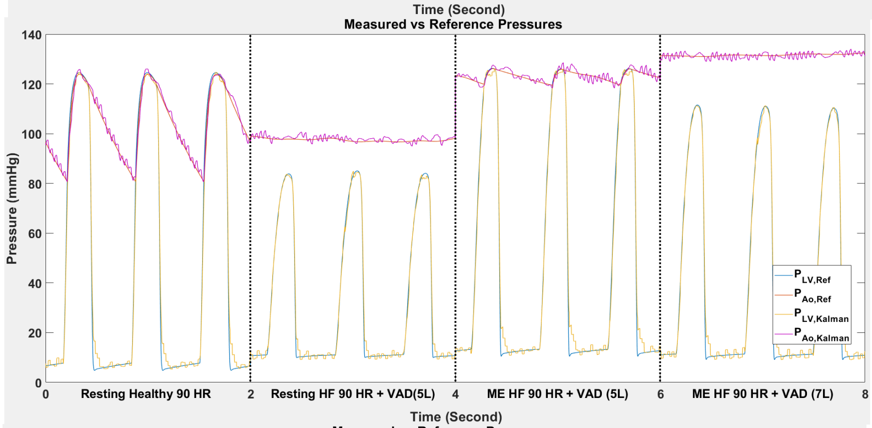

Flow Rate (L/min)
Q_{VAD}
Q_{GP}
HR (bpm) 60 60 60 90 90 90 120 120 120 120
PWM (%) 0.7 0.8 0.9 0.9 0.8 0.7 0.7 0.8 0.9 1
$\bar{\epsilon}_Q$ (L/min) 0.11 -0.09 -0.03 -0.33 0.02 0.16 -0.07 0.17 -0.19 -0.14
$\bar{\epsilon}_V$ (cm) -4.12 -2.55 -1.74 -1.61 -2.73 -3.99 -7.46 -8.02 -8.46 -7.29
Normalized Volume Error (cm)
Volume Error
Time (Second)
Flow Rate (L/min)
Q_{gp}
Q_{VAD}
Condition N/R F/R/0 F/R/3 F/R/4 F/R/0 F/ME/5 F/ME/7
HR (bpm) 60 60 60 60 90 90 90
$\bar{\epsilon}_Q$ (L/min) -0.16 -0.02 -0.03 -0.07 -0.01 0.02 -0.07
$\bar{\epsilon}_V$ (cm) -5.95 -3.21 -7.38 -5.84 -2.62 -3.34 -1.57
Normalized Volume Error (cm)
Volume Error
Time (Second)



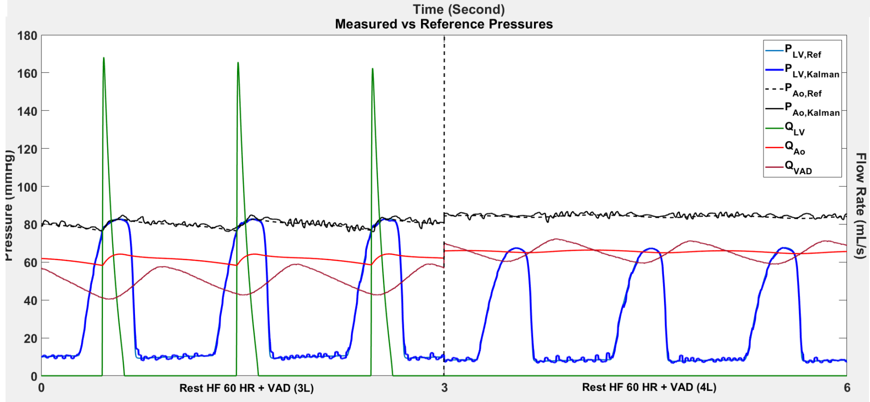
Pressure (mmHg)
Time (Second)



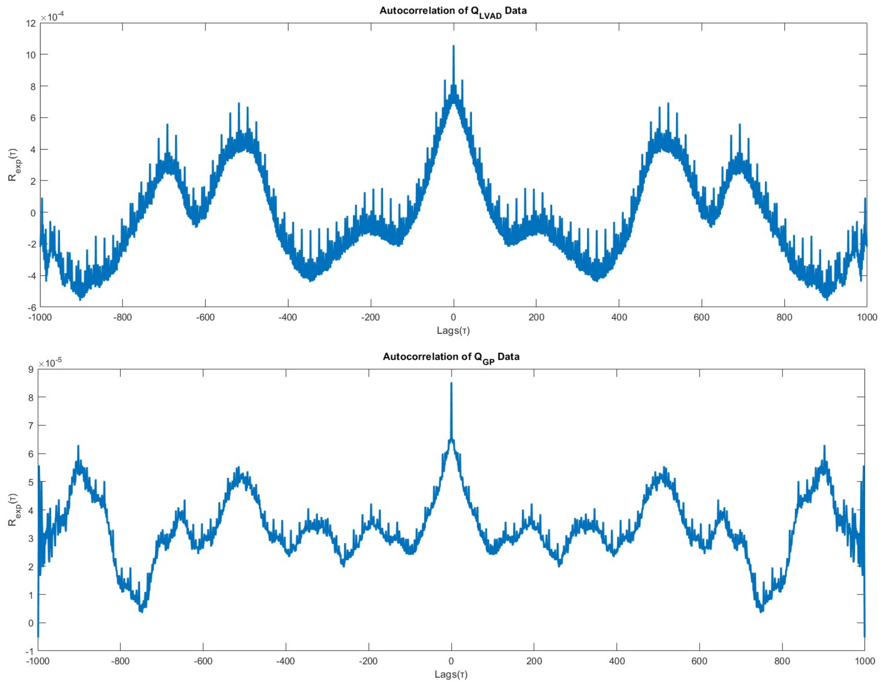
Resting Condition Measured vs Reference Pressures
Pressure (mmHg)
Healthy 60 HR
HF 60 HR
HF 60 HR + VAD (3L)
HF 60 HR + VAD (4L)
Time (Second)



Measured vs Reference Pressures
Pressure (mmHg)
Resting Healthy 90 HR
Resting HF 90 HR + VAD(5L)
ME HF 90 HR + VAD (5L)
ME HF 90 HR + VAD (7L)
Time (Second)



Measured vs Reference Pressures
Flow Rate (mL/s)
Rest HF 60 HR + VAD (3L)
Rest HF 60 HR + VAD (4L)
Time (Second)


Autocorrelation of Q_LVAD Data
×10^-4
R_exp(τ)
Lags(τ)
Autocorrelation of Q_GP Data
×10^-5
R_exp(τ)
Lags(τ)