Declaration

I hereby declare that the work presented in this thesis titled *Processing of Heart Sound Signal to Monitor Cardiovascular Functions in Real-life Scenario* submitted to the Indian Institute of Technology Jodhpur in partial fulfilment of the requirements for the award of the degree of Doctor of Philosophy, is a bonafide record of the research work carried out under the supervision of Dr. Anil Kumar Tiwari. The contents of this thesis in full or in parts, have not been submitted to, and will not be submitted by me to, any other Institute or University in India or abroad for the award of any degree or diploma.

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Certificate

This is to certify that the thesis titled *Processing of Heart Sound Signal to Monitor Cardiovascular Functions in Real-life Scenario*, submitted by *Puneet Kumar Jain (PG201182005)* to the Indian Institute of Technology Jodhpur for the award of the degree of *Doctor of Philosophy*, is a bonafide record of the research work done by him under my supervision. To the best of my knowledge, the contents of this report, in full or in parts, have not been submitted to any other Institute or University for the award of any degree or diploma.

Anil Kumar Tiwari
Ph.D.Thesis Supervisor

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List of Symbols

Symbol	*Description*
abs(l)	Absolute values of the vector *l*
a	Acceleration
A	Approximation coefficients
Ar	Area
α	Scaling parameter
α_{in}	Input vector
β	Scaling parameter
BW	Bandwidth of the signal
C	Capacitance between two plates
C_A	Capacitance on plate A
C_B	Capacitance on plate B
ΔC	Difference between capacitance on plates A and B
d	Distance between capacitive plates
d_o	Initial position of the plate
DW	height of diastolic wave in PPG
D_j	Detailed coefficient vector at level *j*.
D_j^T	Thresholded detailed coefficient vector at level *j*.
D_j^{clean}	Clean (without noise) detailed coefficient vector at level *j*.
ε	Permittivity of the plate-separating material
f	Force
F	Fano factor
f_1	Clean signal
f_2	Denoised signal
fit	Fit coefficient
F_c	Center frequency
F_s	Sampling frequency
g	Acceleration due to the gravity of the Earth
G	Analysis high-pass filter
$\tilde{G}$	Synthesis high-pass filter
H	Analysis low-pass filter
$\tilde{H}$	Synthesis low-pass filter
I	Consecutive upward and downward point
J	Level of decomposition
K	Kurtosis value
l_1	Level 1
l_2	Level 2
m	Mean

m_s	Mass
MAD	Median of absolute value
med_{75}	75th percentile value in absolute sorted vector
MSE	Mean square error
N	Length of the vector
p	Pass-band
Q	Quality factor
Q_i	Quality index for heart sound signal
QT	Electrical systole
QS2	Mechanical systole
r	Redundancy parameter
R	Frequency
s	Scaling factor in wavelet
S	Stop-band
SR	Segmentation rate
SW	height of systolic wave in PPG
t	Shifting parameter in wavelet
T	Threshold value
T_1	Lower threshold value
T_2	Higher threshold value
T_x	Threshold for x-axis signal
T_z	Threshold for z-axis signal
T_{DVP}	Duration between systolic and diastolic peaks
v	Variance
Δx	Displacement in spring position
X	Sparsed signal
$x_{norm}(n)$	n^{th} element in normalised vector *x*
$x_s^T(n)$	n^{th} element in threholded vector *x* using soft threshold function
x(n)	n^{th} element in signal vector *x*
X(k)	DFT coefficient at frequency *R*
Y	Output compressed signal
z	Electric impedance
Z	Integers
μ_w	Mean of a signal over a window *w*
μA	micro-ampere
σ	Noise variance
σ_w^2	Variance of a signal over a window *w*
$\hat{\sigma}$	Estimated noise variance
Ψ_n	Mother wavelet
Ψ	Sparsifying matrix
ϕ	Sensing matrix
δ	*Spring constant*
$\theta(\mathrm{n})$	Transition band function at n^{th} position

List of Abbreviations

Abbreviation	*Full form*
AC	Aortic Valve Closure
ADC	Analog to Digital Converter
AF	Atrial Fibrillation
AHA	American Heart Association
AI	Artificial Intelligence
ALE	Adaptive Line Enhancer
ANC	Adaptive Noise Cancellation
AO	Aortic Opening
AR	Aortic Regurgitation
AS	Aortic Stenosis
ASIC	Application-Specific Integrated Circuit
AWGN	Added White Gaussian Noise
BCG	Ballistocardiography
BAN	Body Area Network
CAD	Coronary Artery Diseases
CC	Capacitive Coupled
CO	Cardiac Output
COPD	Chronic Obstructive Pulmonary Disease
CPR	Cardio-Pulmonary Resuscitation
CS	Compressed Sensing
CSCW	Cardiac Sound Characteristic Waveform
C-TQWT	Constrained-Tunable Quality Wavelet Transform
CVD	Cardio-Vascular Disease
CWT	Continuous Wavelet Transform
DCT	Discrete Cosine Transform
DSP	Digital Signal Processor
DVP	Digital Volume Pulse
DWT	Discrete Wavelet Transform
ECG	Electrocardiography
ECHO	Echocardiography)
E-M	Electro-Mechanical
FHS	Fundamental Heart Sound
F-IMF	First order-Intrinsic Mode Function
FPGA	Field-Programmable Gate Array
GA	Genetic Algorithm
HMM	Hidden Markov Model
HRV	Heart Rate Variability
HT	Hilbert Transform

ICG	Impedance Cardiography
ICU	Intensive Care Unit
IM	Isovolumic Movement
LED	Light Emitting Diodes
LMS	Least Mean Square
LVET	Left Ventricular Ejection Time
MC	Mitral Valve Closure
MD	Mean Deviation
MEMS	Micro-Electro Mechanical System
MFCC	Mel-Frequency Cepstral Coefficient
MI	Myocardial Infarction
MO	Mitral Valve Opening
MR	Mitral Regurgitation
MS	Mitral Stenosis
MSP	Mixed-Signal Processor
MSPCA	Multi-scale Principal Component Analysis
NASE	Normalized Average Shannon Energy
NFC	Near Field Communication
PC	Personal Computer
PCA	Principal Component Analysis
PCB	Printed Circuit Board
PCG	Phonocardiography
PEP	Pre-Ejection Period
PIC	Programmable Interface Controllers
PPG	Photoplethysmography
PS	Pulmonary Stenosis
PTT	Pulse Transit Time
RE	Rapid Systole Ejection
RFID	Radio-Frequency Identification
RI	Reflection Index
rPPG	Remote-Photoplethysmography
SBP	Systolic Blood Pressure
SCG	Seismocardiography
SI	Stiffness Index
SNR	Signal-to-Noise Ratio
STFT	Short Time Frequency Transform
SURE	Stein's Unbiased Risk Estimation
SV	Stroke Volume
TDP	Tosade de Pointes
TEO	Teager Energy Operator
TQWT	Tunable Quality Wavelet Transform
UDFT	Unitary Discrete Fourier Transform
WT	Wavelet Transform