

Contents

	Preface	<i>xi</i>
	List of Symbols	<i>xv</i>
1	Introduction	<i>1</i>
	References	<i>10</i>
2	Single Degree of Freedom System	<i>13</i>
2.1	Introduction	<i>13</i>
2.2	Governing Equations and Solution for Square Pulse Driving	<i>15</i>
2.2.1	Entrance and Exit Effects (Entrance Pressure Drop, Exit Loss)	<i>22</i>
2.2.2	Corrected Speed of Sound	<i>34</i>
2.2.3	Effect of Surface Tension on Resonance Frequency	<i>36</i>
2.2.4	Rayleigh's Method for Calculating the Resonance Frequency	<i>37</i>
2.2.5	Logarithmic Decrement Method to Estimate Damping	<i>38</i>
2.2.6	Bulk Viscosity	<i>40</i>
2.2.7	First Estimate on the Frequency Dependence of Damping	<i>41</i>
2.3	Solution for Ramped Pulse Driving	<i>42</i>
2.4	Solution for Exponential Pulse Driving	<i>47</i>
2.5	Solution for Harmonic Driving and Fourier Analysis	<i>50</i>
2.5.1	Frequency-dependent Damping (Full Solution)	<i>56</i>
2.6	Non-linear Effects Associated with Non-complete Filling of the Nozzle	<i>61</i>
	References	<i>71</i>
3	Two Degrees of Freedom System	<i>75</i>
3.1	Introduction	<i>75</i>
3.1.1	Rayleigh's Method to Determine Approximately the Resonance Frequencies of a Two Degrees of Freedom System for the Case with Surface Tension	<i>79</i>
3.1.2	Calculation of the Damping of Two Degrees of Freedom System with Low Viscosity Using the Logarithmic Decrement Method	<i>84</i>
3.1.3	Flow Through a Conical Nozzle	<i>87</i>
3.1.4	Flow Through a Bell-mouth-shaped Nozzle	<i>91</i>
3.2	Governing Equations and Solutions for Square Pulse Driving	<i>98</i>

3.2.1	Special Cases	101
3.2.2	Solutions for the Low Viscosity Inks to Square Pulse Driving	105
3.2.3	Solutions for Inks with a Moderate Viscosity to Square Pulse Driving	111
3.2.4	Solutions for a High Viscosity Ink to Square Pulse Driving	115
3.3	Solutions for Ramped Pulse Driving	119
3.3.1	Solutions for Low Viscosity Inks to Ramp Actuation	121
3.3.2	Solutions for Moderate Viscosity Inks to Ramp Actuation	122
3.3.3	Solution for Large Viscosity Inks to Ramp Actuation	122
3.3.4	Solution to Ramped Pulse Driving	123
3.4	Solutions for Exponential Pulse Driving	128
3.4.1	Solution for Low Viscosity Inks to Exponential Ramp Driving	130
3.4.2	Solution for Moderate Viscosity Inks to Exponential Ramp Driving	131
3.4.3	Solution for Large Viscosity Inks to Exponential Ramp Actuation	131
3.4.4	Solutions to Exponential Pulse Driving (Pulse Consisting of Two Exponential Ramps)	132
3.5	Solution for Harmonic Driving and Fourier Analysis	134
3.5.1	Frequency Dependent Damping (Full Solution)	144
3.6	Non-linear Analysis	148
3.6.1	Capillary Pressure and Force in Conical Nozzle	157
3.6.2	Capillary Pressure and Force in Bell-mouth-shaped Nozzle	161
	References	163
4	Multi-cavity Helmholtz Resonator Theory	167
4.1	Introduction	167
4.2	Governing Equations	169
4.2.1	Speed of Sound in Main Supply Channel	172
4.3	Solutions for Ramped Pulse Driving for Low Viscosity Inks	174
4.4	Solution for Harmonic Driving and Fourier Analysis	183
	References	192
5	Waveguide Theory of Single-nozzle Print Head	193
5.1	Introduction	193
5.2	Long Waveguide Theory	197
5.2.1	Characteristics of a Closed End/Closed Pump of the Waveguide Type Without Connecting Ducts	202
5.2.2	Characteristics of an Open End/Closed End Pump of the Waveguide Type Without Connecting Ducts	204
5.2.3	Viscous Drag in Non-circular Channels	206
5.3	Solutions for Ramped Pulse Driving of the Waveguide-type Inkjet Pump	207
5.3.1	The Closed End/Closed End Case	207
5.3.2	Damping of the Closed End/Closed End Print Head	216
5.3.3	Open End/Closed End Case	219
5.4	Solutions for Harmonic Driving and Fourier Analysis Including the Effect of Damping	221

- 5.4.1 Solution of Wave Equation with Poiseuille Damping in Nozzle and Throttle 224
- 5.4.2 Sample Calculation and Results for Closed End/Closed End Print Head Channel Arrangement 227
- 5.4.3 Sample Calculation and Results for Open End/Closed End Print Head Channel Arrangement 230
- 5.4.4 Full Solution of Wave Equation Including Frequency-dependent Damping 233
- 5.4.5 Closed End/Closed End Case 238
- 5.4.6 Open End/Closed End Case 240
- 5.5 Non-linear Analysis of the Waveguide Type of Print Head Including Inertia, Viscous, and Surface Tension Effects in the Nozzle 243
 - 5.5.1 Results for the Closed End/Closed End Arrangement 245
 - 5.5.2 Results for the Open End/Closed End Type of Waveguide Pump 246
 - 5.5.3 High Frequency Pulsing, Start-up, and Nozzle Front Flooding 249
 - 5.5.4 Effect of an Air Bubble on the Internal Acoustics of a Print Head 252
 - 5.5.5 Higher Order Meniscus Oscillations 254
- 5.6 Means and Methods to Enhance Fluid Velocity in Nozzle 258
- References 259

- 6 Multi-cavity Waveguide Theory 263**
 - 6.1 Introduction to Multi-cavity Acoustics 263
 - 6.2 Analysis of Cross-talk in an Open End/Closed End Linear Array Print Head with Alternately Activated and Non-activated Pumps 266
 - 6.3 Analysis of Cross-talk in an Open End/Closed End Linear Array Print Head with Alternately One Pump Activated and Two Pumps Idling 277
 - 6.4 Analysis of Cross-talk in an Open End/Closed End Linear Array Print Head with Alternately One Pump Activated and Three Pumps Idling 285
 - 6.5 Analysis of Cross-talk in an Open End/Closed End Linear Array-shared Wall Shear-mode Print Head with Alternately One Pump Activated and Two Pumps Non-activated 297
 - 6.6 Analysis of Cross-talk in a Closed End/Closed End Linear Array Print Head with Alternately Activated and Non-activated Pumps 302
 - References 307

- 7 Droplet Formation 309**
 - 7.1 Introduction 309
 - 7.2 Analysis of Droplet Formation (Positive Pulse) 312
 - 7.2.1 Force (Impulse) Consideration 313
 - 7.2.2 Energy Consideration 316
 - 7.2.3 Droplet Formation Criterion from a Retracted Meniscus 319
 - 7.3 Analysis of Droplet Formation (Negative Pulse) 320
 - 7.3.1 Force Consideration 321
 - 7.3.2 Energy Consideration 324

- 7.4 Deceleration Due to Elongational and Surface Tension Effects Prior to Pinching Off 326
- 7.5 Non-linear Two Degrees of Freedom Analysis Including the Effects of Droplet Formation 332
- 7.6 Non-linear Waveguide Theory Including the Effects of Droplet Formation 335
 - 7.6.1 Results for the Closed End/Closed End Arrangement 336
 - 7.6.2 Results for the Open End/Closed End Type of Waveguide Pump 340
- References 344

8 Droplet Flight, Evaporation, Impact, Spreading, Permeation, and Drying 347

- 8.1 Introduction 347
- 8.2 Evaporation of a Free-flying Droplet Exposed to Still Air 348
- 8.3 Cooling of a Free-flying Droplet During Flight Through Still Air 353
- 8.4 Deceleration of a Free-flying Droplet due to Air Friction 355
- 8.5 Spreading 357
 - 8.5.1 Static Spreading 359
 - 8.5.2 Surface-tension-driven Spreading 362
 - 8.5.3 Inertia-controlled Spreading 366
- 8.6 Permeation into Porous Substrates 389
- 8.7 Evaporation of Dome-shaped Blobs of Fluid 391
- References 393

Appendix A: Solving Algebraic Equations 399

- A.1 Second-order Algebraic Equation 399
- A.2 Third-order Algebraic Equation 399
- A.3 Fourth-order Algebraic Equation 402
- References 404

Appendix B: Fourier Decomposition of a Pulse 407

- B.1 Pulse with Two Ramps 407
- B.2 Exponential Pulse 409
- B.3 Pulse with Three Ramps and Two Stationary Levels 413
- References 416

Appendix C: Toroidal Co-ordinate System 417

- C.1 Introduction 417
- C.2 Definition with Respect to Rectangular Co-ordinate System 417
- C.3 Scale Factors 417
- C.4 Elementary Line Element 418
- C.5 Unit Vectors 418
- C.6 Nabla Operator ∇ 419
- C.7 Gradient of Scalar 419
- C.8 Divergence of a Vector Field 419
- C.9 Dyadic Product $\nabla\nu$ 420

C.10	Laplacian of Vector Field $\nabla \cdot \nabla \nu$ ($\nabla^2 \nu$)	421
C.11	Indefinite Integrals Involving Hyperbolic Functions	422
	References	422
	Index	423

