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Introduction

Droplet-on-demand (DoD) inkjet print heads can be found in a range of different designs, from the single nozzle piezo-driven micropipette (Microdrop (www.microdrop.com), MicroFab (www.microfab.com)) up to print heads with thousands of nozzles integrated (Xaar (www.xaar.com), Seiko-Epson (http://global.epson.com/innovation/core_technology/micro_piezo.html), Fujifilm-Dimatix (http://www.fujifilmusa.com/products/industrial_inkjet_print heads/), HP (www.hp.com), Konica-Minolta (https://www.konicaminolta.com/inkjet/inkjethead/index.html), Memjet (www.memjet.com), Canon (www.canon.com, www.oce.com), Brother (www.brother.com)).

The sub-assembly of the system of which the print head is part of, contains the print head, an ink reservoir of which the pressure is kept a level such that the print head does not leak when idling, an ink conveying supply line and electronics to drive the actuators of the different nozzles. An inkjet print head is an open fluidic system without any valves to control the flow direction. Surface tension and some under-pressure keeps the fluid inside; the main flow direction is controlled by surface tension and inertia forces [1].

Focussing on the mechanism that generates droplets, all print heads are basically the same; behind each nozzle there is a small chamber, and each chamber is connected to the main ink supply, either directly or by a small duct called the throttle. In a piezoelectric-driven print head, part of the wall of the chamber is covered with a piezoelectric platelet. In a bubble jet (thermal) print head, a part of the pump chamber is covered with a small resistor plate [2]. When the piezo platelet is activated in a pulse-wise fashion, a pressure wave is generated that travels towards the nozzle, speeding up the fluid velocity in the nozzle [3]. The velocity is so high that ultimately a droplet or a series of droplets is formed. By applying an electrical pulse to the resistor plate, locally the fluid will be heated and turned into vapour. The sudden formation of the vapour bubble pushes the fluid through the nozzle and results into a droplet or a series of droplets. Viscous dissipation causes the fluid in the nozzle to come to a standstill after a few oscillations. After replenishing of the volume of the droplet(s) by surface tension and asymmetry effects in the nozzle caused by the meniscus motion and emptying of the nozzle due to droplet formation, the system is ready for the next pulse.

The present book is confined to piezo-driven print heads. An example of such a print head is depicted in Figure 1.1.

Design of Piezo Inkjet Print Heads: From Acoustics to Applications,
First Edition. J. Frits Dijksman.

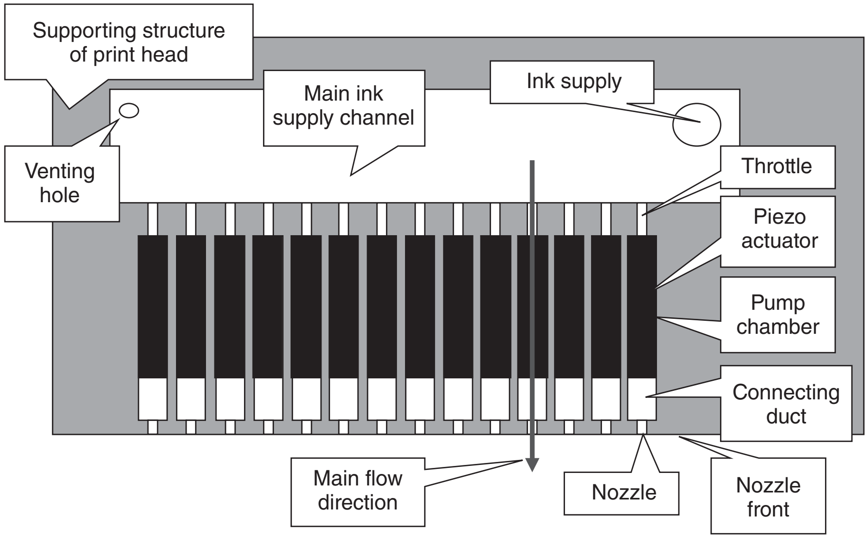

Figure 1.1 Schematic of piezo-driven print head of the Helmholtz type.

A large number of pumps are integrated in a so-called linear array print head. Linear array print heads can be stacked to form a matrix array print head. The dimensions of the print head are usually much smaller than the substrate to be printed. To cover the area of a substrate, several arrangements are possible:

- The print head is mounted on a stationary rig, and the substrate is placed on a so-called XY stage; the substrate is printed in a number of subsequent X and Y motions of the stage.
- The print head is mounted on a carriage allowing for covering the substrate in width direction; the substrate is moved underneath the print head by a linear stage, whose motion is at right angles with respect to the motion of the carriage; the substrate is printed in a number of subsequent carriage motions and stepwise motion of the linear stage.
- A number of print heads are mounted on a stationary rig, such that the width of the substrate is covered; the substrate is placed on a linear stage. The substrate is printed in one continuous motion of the linear stage.

All the pumps are connected to the main supply channel through small channels, called throttles; such a set-up of parts is referred to as the Helmholtz design [4]. The ink flows through the parallel-placed chambers towards the nozzles. The wall of each pump is partly covered with a piezoelectric actuator; upon charging the actuator the volume of the pump chamber is changed causing a change in pressure. The ink is fed to the main supply channel through a feedhole, the ink supply. It is very important to fill the print head without any air bubbles; to visualize this need a venting hole is present. The nozzles are placed at a constant pitch; such a pitch is given in dots per inch (dpi) (1 dpi = 25.4 mm, 100 dpi = 0.254 mm = 254 μm).

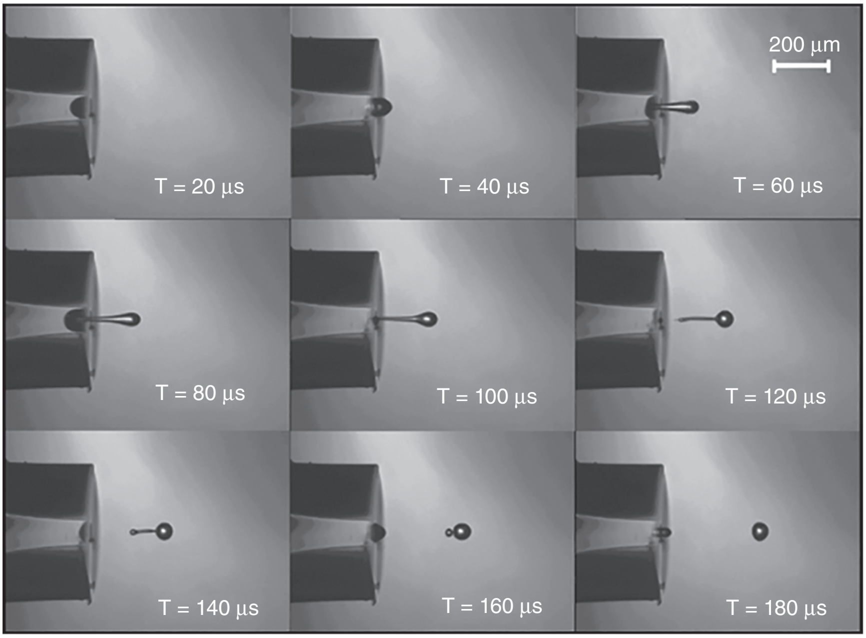

Figure 1.2 Jetting of a low viscosity ink (water) from a Microdrop Autopipette AK 510 with a nozzle of 70 μm. The print head is driven with a negative pulse. Initially the meniscus retracts and then the droplet is formed. The droplet speed is about 2 m s^{-1}; the droplet diameter is about equal to the nozzle diameter. Source: With permission from Microdrop GmbH Germany.

When the print head is driven by pulse-wise actuation, droplet formation starts. A few examples are shown in the next three figures, displaying the jetting of a low viscosity ink, a high viscosity ink, and a viscoelastic ink (an ink made by dissolving a small amount of polymeric material in a low viscosity organic solvent) (Figures 1.2–1.4).

In order to understand the action of a piezo-driven print head, several aspects must be considered:

- The mechanical design of it and the micro-fluidic layout of the fluid path from reservoir all the way up to the nozzle.
- The properties of the ink like density ρ, surface tension γ, speed of sound c, and viscosity μ. For most of the cases to be discussed, these properties will be treated as constants. Ink may contain surfactants; during droplet formation the surface concentration of surfactants at the surface may be reduced, as diffusion from the bulk cannot cope with the fast extension of the surface during droplet formation [8]. Ink may also contain polymer additives that will cause the ink to behave viscoelastically. The fluid properties become rate and history dependent.
- The pulse shape. The electronics of the print head allow for flexibility in choosing the pulse shape.

This book is organized as follows:

In Chapter 2 the print head is modelled as a single cavity with a nozzle, also referred to as a single opening Helmholtz resonator [9]. The pressure inside the

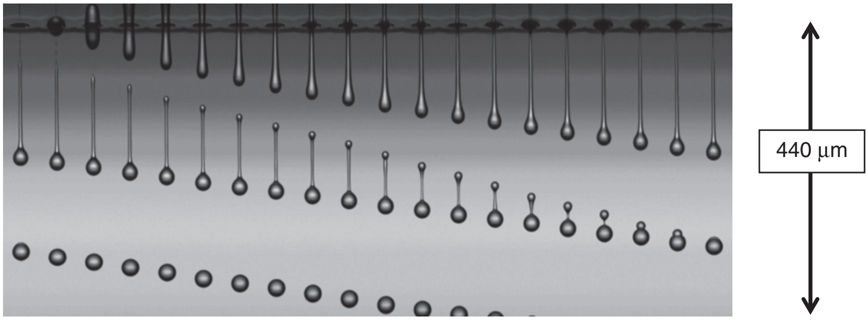

Figure 1.3 Jetting of a high viscosity ink from a prototype print head (Océ Technologies, Venlo, the Netherlands) with a nozzle of 27 μm diameter and driven at 20 kHz with a positive pulse [5]. The ink is silicon oil with viscosity of 9.3 mPa s, density 930 kg m^{-3} and surface tension 20.2 mN m^{-1}. The images were obtained by using a dual-cavity Nd:Yag laser (wave length 532 nm) and fluorescent diffusor to remove any coherence in order to end up with images free of any speckle and interference fringes [6]. The pulse time of the flash has a duration of 8 ns. The picture is a concatenation of images taken with increasing delay from the leading edge of the pulse with steps of 2.5 μs. The droplet speed after the tail has merged with the main droplet is 3 m s^{-1}. The droplet size measures 9.3 pl. Source: With permission from van der Meulen 2015 [5].

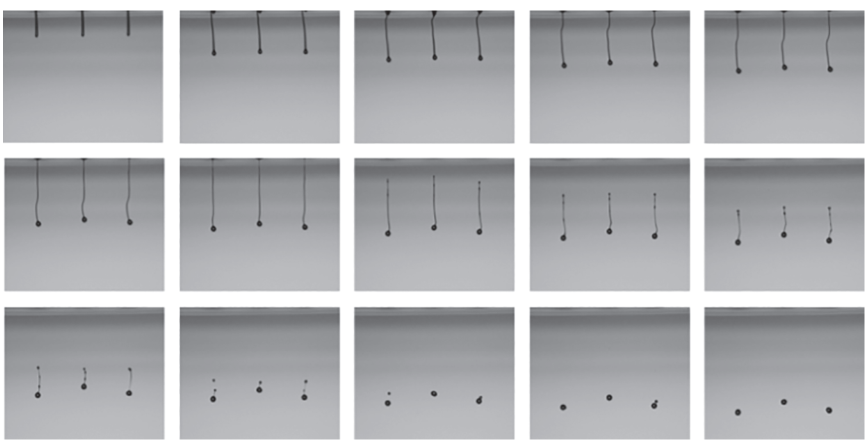

Figure 1.4 Jetting of a viscoelastic ink. Series of photographs showing the evolution of the droplet formation of a viscoelastic ink from a Dimatix Galaxy 256 nozzle print head with 30 μm diameter nozzles [7]. The pitch between nozzles is 254 μm; the timing starts at 10 μs after the leading edge of the pulse, followed by images 10 μs apart in time. The shear viscosity of the ink has been tuned to 10 mPa s. The surface tension measures 30 mN m^{-1}. The final droplet volume equals 15 pl, its speed 2 m s^{-1}.

cavity follows the motion of the fluid in the nozzle and can be altered on demand by a piezoelectric actuator. Such a system will be described by a single degree of freedom oscillator (see Figure 1.5).

The mass of the oscillator is equal to the fluid contained in the nozzle, the stiffness comes from the compressibility of the ink in the pump chamber, and the damping is caused by the viscous drag experienced by the ink in the nozzle.

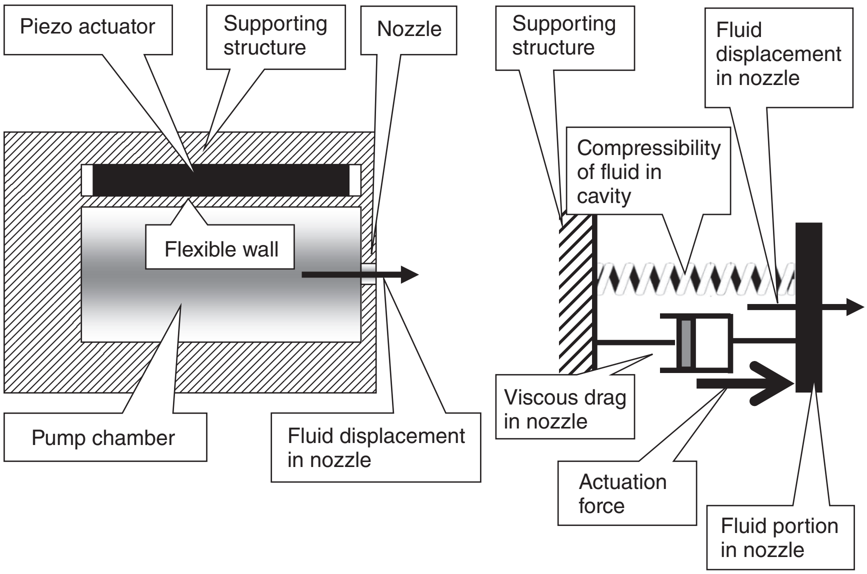

Figure 1.5 Single degree of freedom Helmholtz resonator modelled as a single mass–spring–damper oscillator. The spring models the compressibility of the fluid contained in the pump chamber, the damper is the viscous drag of the ink moving through the nozzle, and the mass is the fluid in the nozzle. By actuation a pressure is built up loading the mass in the nozzle by a force (pressure times surface area nozzle).

With such a set-up, resonance phenomena can be explained and the effects of different pulse shapes, such as a square pulse, trapezoidal pulse, asymmetric pulse, and an exponential pulse; see Figure 1.6.

Different solution strategies will be applied, such as the direct solution of the governing equation, leading to the understanding of oscillatory behaviour, critical damping and overdamping. The equation of motion is linear making solution by Fourier analysis possible, opening the route to investigate in detail the influence of pulse shape, repeat rate and the dependence of viscosity on frequency.

The nozzle is a short channel and entrance and exit effects cannot be discarded. Effects like the influence of surface tension on the resonance frequency and the speed of sound corrected for the compliance of the structure of the print head surrounding the pump chamber will be handled in separate sections, including alternative methods to calculate the resonance frequency and the effect of damping.

At the end of the nozzle, the fluid makes an interface with the surrounding air, and a meniscus is formed [10]. When the print head is not functioning, the meniscus is stationary, and its shape is determined by the equilibrium of the set suction pressure by the pressure controller and the height of the fluid column above the nozzle front. Usually the suction pressure is set such that meniscus is slightly retracted, preventing the print head from leaking ink during idling. When upon actuation the meniscus retracts further into the nozzle, the curvature increases and the capillary pressure increases. This effect forces the meniscus to move back to its original position. During outflow the same happens. With

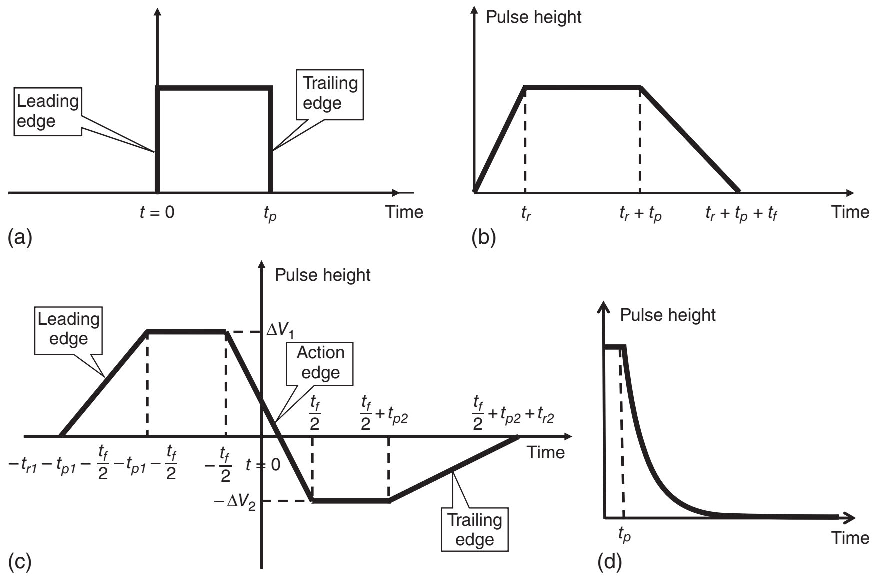

Figure 1.6 Different pulse shapes. (a) square pulse. (b) asymmetric trapezoidal pulse with different rise and fall times. (c) asymmetric double pulse with a steep action edge. (d) asymmetric exponential pulse of which the leading edge is given by a small time constant and the trailing edge by a large time constant.

increasing outflow the curvature increases, and the capillary force opposing the motion increases accordingly. For small displacements (with reference to the nozzle radius), the capillary action builds a kind of linear mechanical spring action with a fixed spring constant. The restoring force is a linear function of the meniscus displacement. For larger displacements of the meniscus, however, the restoring force becomes a non-linear function of the displacement. When the meniscus retracts into the nozzle, the capillary pressure increases up to the position where the curvature becomes equal to the radius of the nozzle. From that moment on the capillary pressure stays constant. During outflow the same happens. With increasing outflow the curvature increases, and the capillary force opposing the motion increases as well. This holds true as long as the meniscus stays pinned to the rim of the nozzle and the amount of ink outside the nozzle is limited. When more fluid flows slowly outwards, a stationary droplet will be formed whose curvature is larger than the radius of the nozzle and the restoring force drops. At the very moment the ink starts to wet the nozzle front; the capillary force drops quickly to zero. The capillary action builds a kind of mechanical spring action with a non-linear spring constant. This non-linear spring constant depends on the position of the meniscus. When the meniscus retracts, the surface tension force becomes limited, and because of the fact that the fluid column becomes shorter, less inertia force is involved in the dynamics and also the viscous drag is reduced. Approximately the same happens for the case the meniscus moves outwards; the opposing force due to surface tension is limited, but the inertia force becomes bigger. As the length of the nozzle is constant, the viscous drag remains constant. These non-linear effects complicate the solution of the equation describing the fluid motion in the nozzle caused by pressure fluctuations induced by the pulse-wise charging of the piezoelectric actuator. The equation of motion can only be solved by numerical integration.

The single degree of freedom theory is the most simple approach to understand the basic behaviour of a print head. This one degree of freedom theory will be extended by increasing the complexity in a number of consecutive steps:

- Adding the throttle, leading to a two degrees of freedom oscillator.
- Considering more pumps working in parallel, resulting in a five degrees of freedom system.
- Taking into account the fact that the pump chamber is in fact a waveguide, with an infinite number of modes.
- Handling non-linear effects and non-straight cylindrical nozzles.

In Chapter 3 the print head is treated as a two degrees of freedom Helmholtz resonator with two openings. One opening is the nozzle and the other being the throttle (see Figure 1.7).

The actuator force depicted in Figure 1.7 is pressure times surface area, so the force on the nozzle mass may differ from the force acting on the throttle mass, because the respective surface areas may differ.

The two equations of motion will be solved by either the direct method or Fourier analysis. The direct solution reveals the complicated interaction of the damping characteristics of the throttle and the nozzle. The non-linear effects caused by the motion of the fluid in the nozzle will be handled by the non-linear theory. In Chapter 3 in addition the hydrodynamics in non-straight cylindrical nozzles will be discussed, such as the conical nozzle and the bell-mouth-shaped nozzle.

In Chapter 4 the theory will be extended to the description of the interaction between pumps in a multi-nozzle print head. This concerns the acoustic cross-talk between driven and non-driven nozzles, communicating with each other through the main supply channel. In the case that all pumps are equal and that a number of pumps are activated at the same time and in the same manner, the governing set of equations of motion reduces to a set of five equations of motion. The coefficients of these equations, however, depend on the number of pumps activated. The five degrees of freedom are the motions of the fluid portions in the nozzle and throttle of the active pumps, the motions of the fluid portions in the nozzle and throttle of the inactive pumps and the fluid motion in the connection of the print head to the ink supply line, called the hose pillar.

Up to now the print head is considered to be built up out of a large number of equal sized piezo-driven Helmholtz-type of pumps, placed parallel and all connected to the main supply channel by means of throttles. In order to have a design with a small nozzle pitch, the pumps are placed as closely as possible next to each other. This means that the length of the pump chamber has to be long compared with its cross-sectional dimensions in order to generate enough volume displacement by the piezoelectric actuator. Rather than a Helmholtz resonator, the design looks like waveguide. The basic layout of such a waveguide type of pump is shown in Figure 1.8.

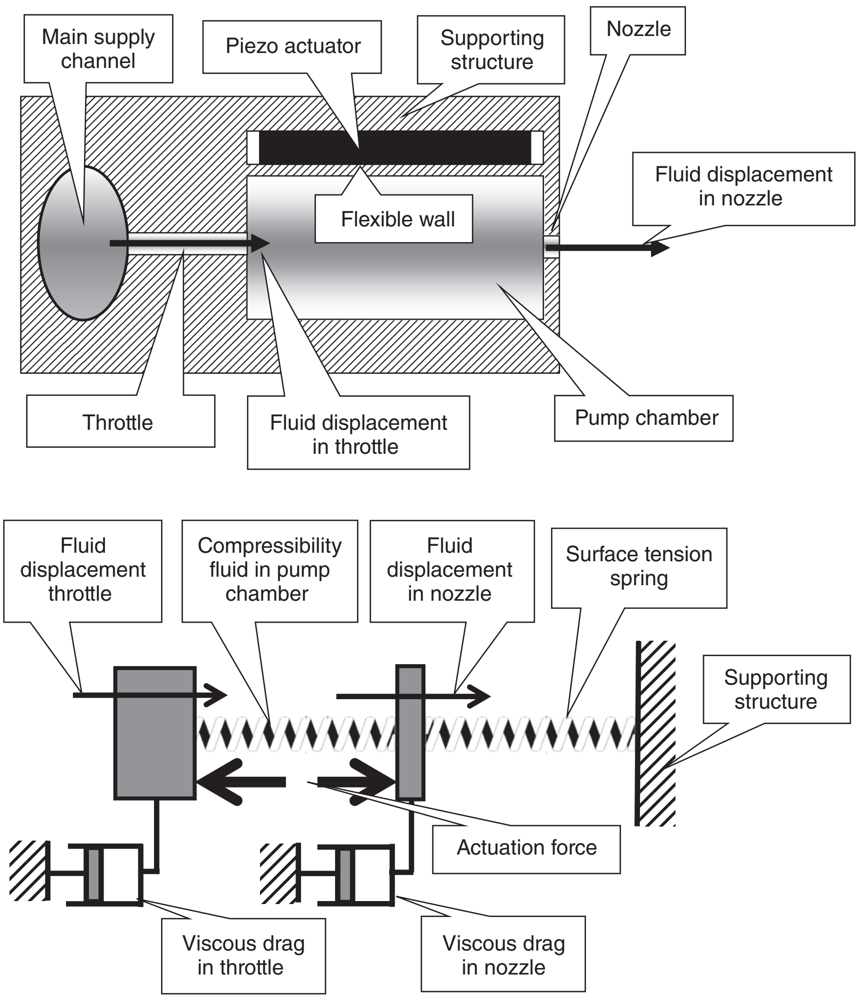

Figure 1.7 Schematic of single nozzle print head (or a specific pump out of a multi-nozzle print head) modelled as a two degrees of freedom oscillator. The oscillator has two masses, the mass of the fluid contained in the throttle and the mass of the fluid contained in the nozzle. The fluid in the nozzle is connected by a surface tension spring to the supporting structure and by another spring to the mass in the throttle by the compressibility of the fluid in the pump chamber. The fluid portions in the throttle and the nozzle undergo viscous drag upon motion. The actuator force works both on the mass in the throttle and the mass in the nozzle.

The waveguide-type pump consists of a pump chamber and a nozzle and either an open connection to the main supply channel or a throttle. With an open connection to the main supply channel, such a design will be referred to as the open end/closed end arrangement. When a throttle is present, the design is referred to a closed end/closed end. For the Helmholtz type of print head, it makes no sense to leave the throttle out, to have a direct connection to the main supply channel; no pressure fluctuations can be generated. For the waveguide design, however, it is possible to have an open connection to the main supply channel. By actuation

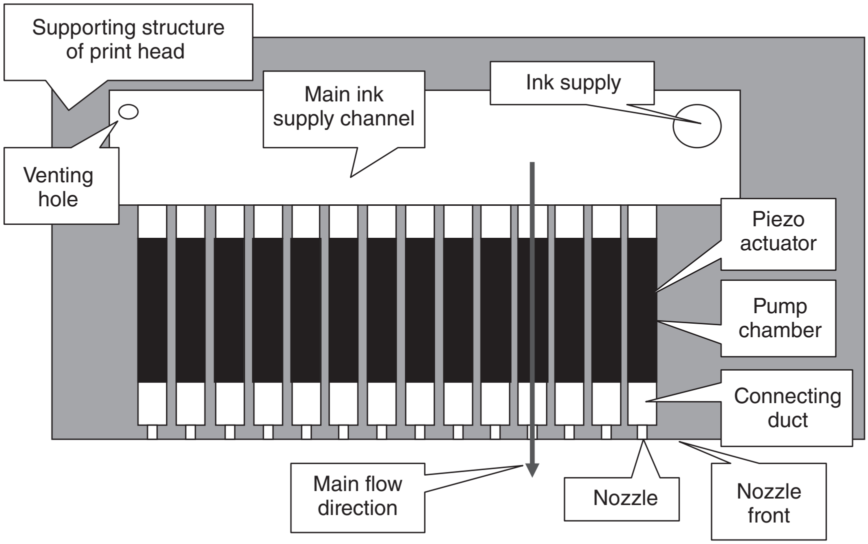

Figure 1.8 Basic layout of a closed end/open end multi-nozzle print head with pump chambers of which the length is large compared with the cross-sectional dimensions. The connecting duct towards the nozzle and the connection to the main ink supply channel may both have different cross-sectional dimensions compared with those of the pump section. The arrow symbolizes the main flow direction.

pressure waves will be induced that travel back and forth through the waveguide, their evolution in time depending on the reflection characteristics at the open end to the main supply channel and at the nozzle. In Chapter 5 the behaviour of one single pump is analysed. Key questions like the response in the frequency domain and the response in the time domain upon pulse-wise actuation will be answered. To incorporate the non-linear effects caused by the surface tension, inertia and damping effects in the nozzle all depending on the extent of filling, the waveguide is divided into a large number of separate parts of finite length. The resulting set of equations is solved numerically.

In Chapter 6 the waveguide theory for one single pump is extended to a manifold of pumps integrated in a multi-nozzle print head. To reduce the complexity of the calculations, use has been made of symmetry arguments.

Chapter 7 deals with droplet formation. At the end of Chapter 7, the connection is made between the calculated responses in the time domain and droplet formation. For the pump, droplet formation means that fluid has left the system. As this is a fast process, the acoustics of the pump experience droplet formation as a sudden shock and react accordingly.

Chapter 8 is devoted to an exposé of theories on the landing of the droplet on the substrate.

Results will be reported in the natural units applicable for piezo print heads: pressure in bar (10^5 Pa), length in mm (10^{-3} m), cross-sectional dimensions in μm (10^{-6} m), frequency in kHz (10^3 Hz), meniscus velocity in m/s, meniscus displacement in μm (10^{-6} m), droplet speed in m/s and droplet volume in pl (10^{-15} m^3 or 10^{-12} l).

References

1 Knight, E. and Lynn, C. (2010). *Industrial Inkjet for Dummies*. Wiley Publishing, Inc.

2 (a) Wijshoff, H. (2008). Structure- and fluid-dynamics in piezo inkjet print heads. Thesis. Twente University, The Netherlands.
(b) Hutchings, I.M. and Martin, G. (2013). Fundamentals of inkjet technology. In: *Inkjet Technology for Digital Fabrication* (ed. I.M. Hutchings and G.D. Martin), 21–44. John Wiley & Sons Ltd.
(c) Morita, N. (2012). Thermal inkjet. In: *Inkjet-Based Micromachining* (ed. J.G. Korvink, P.J. Smith and D.-Y. Shin), 41–56. Wiley-VCR.
(d) Morita, N., Khalate, A.A., Buul, A.M., and van Wijshoff, H. (2016). Inkjet printheads. In: *Fundamentals of Inkjet Printing* (ed. S.D. Hoath), 57–92. Wiley-VCR.
(e) Rosario, T. (2017). Concepts and strategies to adapt inkjet printing to industrial application requirements. In: *Handbook of Industrial Inkjet Printing: A Full System Approach* (ed. W. Zapka), 241–252. Wiley-VCR.
(f) Corrall, J. (2017). Konica Minolta's inkjet printhead technology. In: *Handbook of Industrial Inkjet Printing: A Full System Approach* (ed. W. Zapka), 253–284. Wiley-VCR.
(g) Brünahl, J., Condie, A., Crankshaw, M. et al. (2017). Xaar's inkjet printing technology and applications. In: *Handbook of Industrial Inkjet Printing: A Full System Approach* (ed. W. Zapka), 285–312. Wiley-VCR.
(h) Simske, S.J. (2017). Hewlett Packard's inkjet printhead technology. In: *Handbook of Industrial Inkjet Printing: A Full System Approach* (ed. W. Zapka), 313–335. Wiley-VCR.
(i) Puyot, M. (2017). Memjet's inkjet printhead technology and associated printer components. In: *Handbook of Industrial Inkjet Printing: A Full System Approach* (ed. W. Zapka), 335–350. Wiley-VCR.
(j) Piatt, M., Bugner, D., Chwalek, J., and Katerberg, J. (2017). KODAK's stream inkjet technology. In: *Handbook of Industrial Inkjet Printing: A Full System Approach* (ed. W. Zapka), 351–360. Wiley-VCR.

3 (a) Lee, F.C., Mills, R.N., and Talke, F.E. (1984). The application of drop-on-demand ink jet technology to color printing. *IBM J. Res. Develop.* 28 (3): 307–313.
(b) Bogy, D.B. and Talke, F.E. (1984). Experimental and theoretical study of wave propagation phenomena in drop-on-demand ink jet devices. *IBM J. Res. Develop.* 28 (3): 314–321.
(c) Dijksman, J.F. (1984). Hydrodynamics of small tubular pumps. *J. Fluid Mech.* 139: 173–191.
(d) Dijksman, J.F. and Pierik, A. (2013). Dynamics of piezoelectric print-heads. In: *Inkjet Technology for Digital Fabrication* (ed. I.A. Hutchings and G.D. Martin), 49–60. John Wiley & Sons.

4 (a) Helmholtz, H. (1885). *On the Sensations of Tone as a Physiological Basis for the Theory of Music*. Dover Publications Published in 1954.

(b) Benade, A.H. (1976). *Fundamentals of Musical Acoustics*. Dover Publications Published in 1990.

5 van der Meulen, M-J. (2015). Meniscus motion and droplet formation in inkjet printing. PhD thesis. University of Twente, The Netherlands.

6 van der Bos, A. (2011). Air entrapment and drop formation in piezo inkjet printing. PhD thesis. University of Twente, The Netherlands.

7 Dijksman J.F. and Duineveld P.C. (2015). Droplet-on-demand printing of polymer solutions, Proceedings NIP/DF 2015 Conference Philadelphia, pp 214–218.

8 (a) Stückrad, B., Hiler, W.J., and Kowalewski, T.A. (1993). Measurement of dynamic surface tension by the oscillating droplet method. *Exp. Fluids* 15: 332–340.

(b) Grigorieva, O.V., Kovalchuk, N.M., Grigoriev, D.O., and Vollhardt, D. (2004). Spontaneous non-linear surface tension oscillations in the presence of a spread surfactant monolayer at the air/water interface. *Colloids Surf., A* 250: 141–151.

(c) Grigorieva, O.V., Grigoriev, D.O., Kovalchuk, N.M., and Vollhardt, D. (2005). Auto-oscillation of surface tension: heptanol in water and water/ethanol systems. *Colloids Surf., A* 256: 61–68.

(d) Staat, H.J.J., van der Bos, A., van den Berg, M. et al. (2017). Ultrafast imaging method to measure surface tension and viscosity of inkjet printed droplets in flight. *Exp. Fluids* 58 (2): doi: 10.1007/s00348-016-2284-8.

9 Strutt, J.W. (Baron Rayleigh)(1945). *The Theory of Sound*, vol. 2, 170–172. Dover Publications (reprint of the 1896 edition published by The MacMillan Company).

10 De Gennes, P.G., Brochart-Wyart, F., and Quéré, D. (2003). *Capillarity and Wetting Phenomena, Drops, Bubbles, Pearls, Waves*. Springer.