Acoustic Phenomena in a Demand-Mode Piezoelectric Ink-Jet Printer

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Abstract

This paper addresses acoustic wave propagation in a piezoelectric ink-jet printer. Acoustic resonances limit the operating frequency in inkjet devices and influence the timings of the electrical drive signals. In this study, the resonant frequencies in a multichannel printhead are determined through feedback from the fluid to the piezoelectric structure using an electrical impedance anylyzer. The influence of channel length on resonant frequency is analyzed in a specially constructed printhead. In addition, the effect of different end conditions on the acoustic resonance of the channels was observed.

Because the channels walls are compliant, the propagation of acoustic pressure waves in them is slower than the speed of sound in the fluid, which is a fluid property. The electrical impedance measurements allow the determination of the effective speed of sound in the channel and the optimal timing for the driving electrical signal.

In operation, the drop velocity can be modified by changing the duration of the electrical pulse sent to the piezoelectric actuator. The timing that produces the maximum drop velocity can be also related to the effective speed of sound in the channel. Comparison of the two data sets show that a printhead channel has an acoustical behavior closer to an open-open pipe.

Introduction

The printing industry has an increasing demand for high throughput, reliable, and low cost printers. This is true both for the industrial printers and for the office printers.

Many office and industrial printers operate using drop-on-demand (DOD) mode, in which drops are generated only when needed. DOD printers are based on sudden vaporization of the ink (bubble jet) or sudden movement of the walls of the ink passage. In most cases the wall movement is produced by a piezoelectric element. The present work analyzes the DOD printers using piezoelectric actuators. Optimization of the printer performance, especially at high frequencies of operation, requires good understanding of the acoustic phenomena in the printhead.

Print quality is directly related to the drop formation and a high quality print requires a stable drop with no *satellites* (smaller drops trailing the main drop). The drop is formed as an integration over time of the fluid velocities at the orifice. Drop characteristics are a function of both the fluid properties (surface tension and viscosity) and the fluid flow at the orifice. The later is a direct result of the orifice/nozzle configuration and the pressure waves reaching the orifice. Satellites are produced by secondary reflections of the acoustic pressure waves propagating in the channel. To eliminate the satellites, the reflected acoustic waves need to be damped quickly. This can be done by adjusting the fluid properties, changing the geometry of the ink passage or adjusting the driving signal of the piezoelectric element.

By adjusting the timings of the signal applied to the piezoelectric actuator to match the acoustic propagation, a reduction of the signal amplitude (voltage) is achieved and consequently the power used by the printer is reduced. The correlation of the driving waveform and the timing of the acoustic propagation in the printhead makes it possible to produce drops with smaller diameters than the orifice diameter (drop size modulation) and thus increase the print resolution for a fixed orifice diameter.

All the optimization activities described above require knowledge of acoustical phenomena in the printhead. This work addresses the acoustics in a shared wall, shear mode piezoelectric DOD printhead.[1,2,3] The analysis includes the effective speed of sound in the ink channels, the influence of end effects on the channel acoustics, the correlation between optimum driving parameters, drop volume and velocity and the channel length.

Theoretical Background

The propagation of the sound in fluids in elastic conduits does not take place at the intrinsic speed of sound of the fluid. The propagation speed is reduced due to the lateral compliance of the conduit walls. A relationship between the intrinsic speed of sound c_0 (propagation in an infinite fluid) and the effective speed of sound c in a channel with compliant walls is[4]

$$c = \frac{c_0}{\sqrt{1 + B\gamma}} \qquad (1)$$

The tube compliance γ represents the relative area change of the channel cross section when a unitary pressure is applied on the inner surface. B represents the bulk modulus of elasticity of the fluid $B = \rho c^2$. The reduction of the effective speed of sound from the intrinsic speed of sound increases with the increase in tube compliance.

The fundamental resonance frequency in an open-open pipe can be determined as

$$f_r = c/(2l') \quad (2)$$

where l' is the corrected length for end effects. The corrected length can be determined for open-open pipes as[5]

$$l' = l + 0.61\, d \quad (3)$$

In case of circular cross section d represents the diameter while for rectangular cross section we will take d as the smallest dimension of the rectangle.

For an open – closed pipe the equation (2) becomes

$$f_r = c/(4l') \quad (4)$$

with no corrections applied to the closed end.

If the fundamental resonance frequency can be determined, equations (2) or (4) provide the means to determine the effective speed of sound within the fluid channel. The resonance frequency can be determined with an electrical impedance analyzer through the coupling between the electrical circuit defined by the piezoelectric element and the fluid inside the channel.[6] The same principle can be applied to the channel configuration considered for this study.

We have used the resonance measurement through the fluid/structure coupling to determine the acoustic properties of the printhead. The analysis looks at the effect of the channel length and boundary conditions (end effects produced by the supply manifold and the orifice plate) in terms of the resonance frequency/period. These two ways of determining the speed of sound are compared with the values obtained from optimal driving conditions that are presented in the next section.

Printhead Construction

The printhead analyzed consists in a series of channels that are sawn in a piezoelectric block that consists of a thin piece piezoelectric material bonded to a thicker base piece. Both pieces are poled along a direction perpendicular to the fluid channel. An orifice plate is bonded at the outlet of the channels, and fluid is supplied to a manifold at the back of the printhead. The supply manifold was tilted 51 degrees with respect to the fluid channels, thus creating a printhead with channels of different lengths.

Figure 1 presents the actuating structure (left) and a cross section through a fluid channel (right). To create a drop an electrical signal is applied to the bond layer between the base and the thin piece on one wall with the mirror signal on the bond of the opposite wall while the top is held at 0V. The resulting electrical fields produce the "instantaneous" deformation of the piezoelectric structure which is coupled to the fluid, thus generating acoustic waves that propagate along the channels.

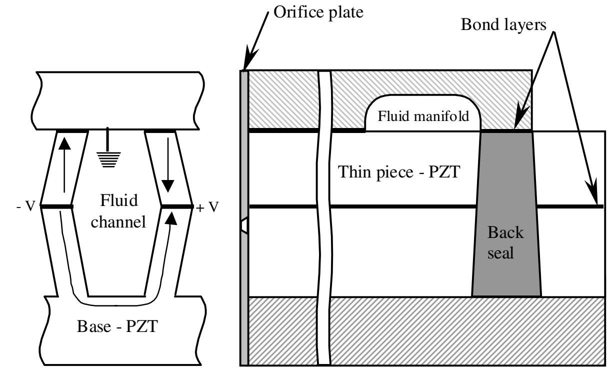

Figure 1. Printhead construction

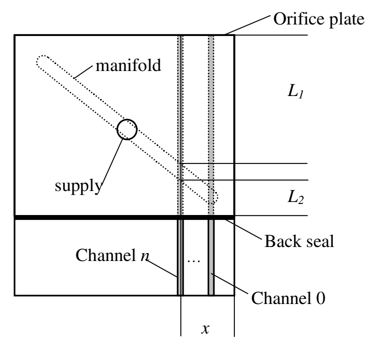

Figure 2. Length of the printhead channels

In these tests, the channel is 360µm deep and 85µm wide. A total of 121 channels are sawn across the printhead. The orifice diameter is 45 µm.

For acoustical purposes the channel is defined lengthwise by the orifice plate at one end and the supply manifold at the other end. When data are collected without the orifice plate or the back seal, the constant (atmospheric) pressure at that boundary determines the acoustical termination of the channel. The printhead used in this work had a slanted manifold (Figure 2). The manifold separates the channel in a front part of decreasing length L_1 and a back part of increasing length L_2 for increasing channel number. Drops are generated by the front part of the channel but acoustic resonance is detected for both regions.

Acoustic Resonance Measurements

From an acoustical perspective the two parts of the channels are independent resonant pipes with the manifold providing an open end condition for both. Measurement of the acoustic resonance in the channels was done for different stages of the printhead construction: printhead without orifice plate and back seal, with orifice plate and without back seal, and with orifice plate and back seal.

A frequency sweep with the electrical impedance analyzer connected to the bond areas at the middle of the channel walls shows the acoustic resonance frequency in both parts of the channel. A typical result for a channel filled with isopropyl alcohol is presented in Figure 3.

On both the phase angle and the impedance curves we can observe three locations that exhibit resonance characteristics. The middle one corresponds to the mechanical structure while the other two are produced by the acoustic resonance in the two parts of the fluid channel: resonant frequency 1 corresponds to the longer part of the channel and resonant frequency 2 corresponds to the shorter part. A sequence of plots from channel 0 to 120 would show the resonant frequency generated by the front part of the channel moving towards the right (increasing), passing the structural resonant frequency and continuing to move towards the right as the length of the front part reduces. The resonant frequency generated by the front part moves in the opposite direction (increasing length).

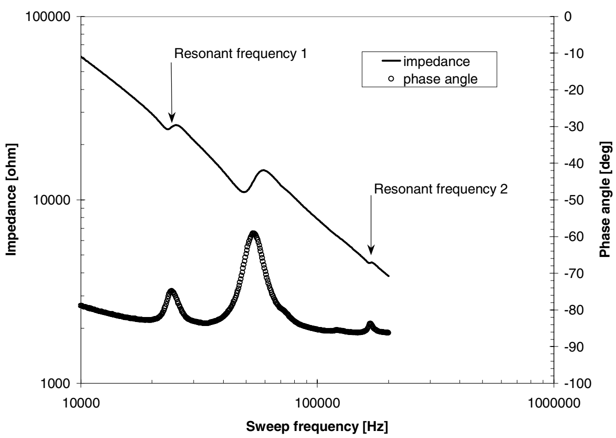

Figure 3. Frequency sweep - impedance and phase angle

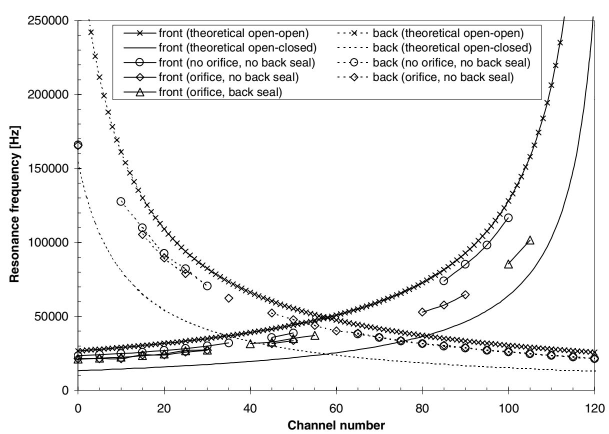

Figure 4. Comparison of resonant acoustic frequencies for different boundary conditions

Figure 4 presents a summary of the acoustic resonant frequencies measured for various boundary conditions. The theoretical curves use equations (2) and (4) for the front and back part of the channel respectively. The compliance (5.81×10^{-10} Pa^{-1}) was determined from the structural analysis of the channel cross section using ANSYS and the measured lengths were corrected using the channel width as the characteristic dimension.

The dotted lines correspond to the back part of the channels and the solid lines to the front of the channel. The curves are also identified by the instance in the fabrication process when data was collected. Very little differences are observed in the resonant frequency for the back part of the channel with and without orifice plate. The resonance peak was no longer observed for the back part of the channel after back seal. Resonance frequency values are closer to the open-open theoretical curve than to the open-closed one.

For the front part of the channels, the frequencies without orifice and no back seal are even closer to the theoretical open-open curve compared to the back part of the channel. This is most likely because the end of the back part of the channel where the seal is applied continues with the channel in the base even when not back sealed, so is not truly open. A larger length correction should be used for the open end of the back part of the channel. After the orifice plate is mounted the resonant frequency shifts towards the theoretical open-closed curve. The theory for organ pipe resonances,[5] being the solution to an eigenvalue problem, allows only for a discontinuous jump in resonant frequency as the terminal impedance changes.

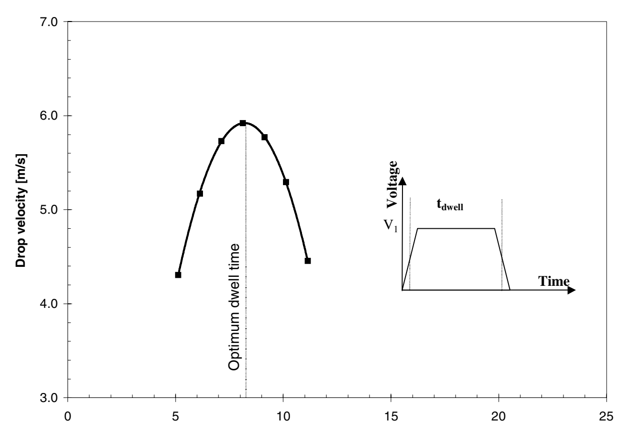

Figure 5. Drop velocity as a function of dwell time - channel 79

Timings for Optimum Driving Conditions

The functional characterization of the printhead was performed with isopropyl alcohol at 60 Hz. Actuation of the piezoelectric structure was done with a trapezoidal waveform as presented in Figure 5. The time at high voltage (dwell time) is measured for practical purposes between the middle of the two transition periods. The increasing ramp of the trapezoidal correspond with an expansion of the channel cross section with the decreasing ramp corresponding to a decrease in channel cross section. During the expansion a negative pressure wave travels to the supply end where it reflects as a positive pressure wave.

The optimum timing is defined as the dwell time for which a maximum velocity is achieved for a constant applied voltage. Based on the wave propagation in the channel (the fall should reinforce the high pressure wave reflected from the supply manifold) the optimum timing is determined from the time it takes the wave to travel to the supply end and back

$$t_{opt} = l'/c \quad (5)$$

In the formula *l'* is the channel's corrected length and *c* is the effective sound speed in the channel. Figure 5 presents the drop velocity as a function of the dwell time. When the fall from high voltage to zero voltage is before or after the reflected waveform reaches the middle of the channel some cancellation occurs resulting in a loss of energy. The optimum dwell time is determined by the maximum in the drop velocity curve presented in Figure 5. It is important to note that the reduction in channel length results in a smaller drop size, thus being a tool to generate smaller drops with the same orifice diameter.[7] Another advantage of a reduced channel length is the ability to increase the operating frequency.

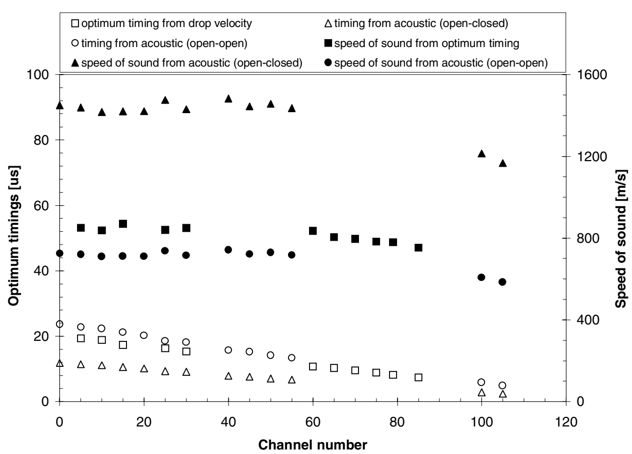

Figure 6. Optimum dwell time and speed of sound

Figure 6 shows the optimum timing and the speed of sound as a function of channel number (linear with the channel length). The filled symbols refer to the speed of sound in the channel and the unfilled symbols describe the optimum dwell time. Optimum dwell time derived from drop velocity measurements (square) is used to derive the effective speed of sound (filled square) from equation (5).

The acoustic resonant frequency from the electrical impedance measurement of the front part of the channel (with orifice plate) is used in equations (2) and (4) to determine the speed of sound in the channels assuming an open-open and an open-closed pipe, respectively. The two values for the speed of sound are used in equation (5) to determine the corresponding optimum dwell time (triangular symbol for open-closed and circular symbol for open-open).

From this comparison we can conclude that the channels of an operational printhead behave from an acoustical perspective more like an open-open tube.

Conclusions

Electrical impedance measurements were used to evaluate printhead acoustics and showed that a fluid channel does not behave as a truly open-closed tube. The same behavior was identified from the optimum timings for the driving waveform. This could be a result of the presence of the orifice and of the compliance of the orifice plate itself.

This study shows that the optimum timing of the driving waveform can be reasonably approximated using the effective speed of sound derived from the acoustic resonant frequencies (impedance measurements). Another option is to use the speed of sound derived using the channel compliance and the speed of sound of the infinite fluid. Both ways lead to slightly longer dwell time values.

Experimental results also showed that by reducing the channel length the optimum waveform duration decreases allowing operation at higher frequencies. Another advantage of shorter channels consists in the ability to generate drops with a smaller diameter than the orifice diameter.

References

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Biography

Bogdan Antohe received an Engineer Diploma from University of Galati, Romania in Shipbuilding Systems in 1991 and a Ph.D. in Mechanical Engineering from Southern Methodist University in 1996. His expertise is in the field of fluid flows and heat transfer in both clear fluid and porous media. At MicroFab, he contributed to the development of the piezoelectric dispensers for ink, Solder Jet, and bio applications by modeling and numerical simulations of the processes within the micro dispenser.

David Wallace has a M.S. from Southern Methodist University and a Ph.D. from University of Texas at Arlington. He has 26 years experience in the design, analysis, and testing of complex fluid flow phenomena. He has published over 50 reports, papers, and presentations covering this work, has been awarded 15 patents, and has 10 more applications pending, all covering ink-jet designs or applications. Dr. Wallace is currently MicroFab's Vice President for technology development.