A Coupled Field Analysis of an Ink Jet Printhead with Shear Mode Piezo Transducer

Yong Zhou
Spectra, Inc.
Hanover, New Hampshire

Abstract

In a shear mode piezo printhead, a piezoelectric driver mechanism is used to deflect one pressure chamber wall and eject a drop of ink from the orifice connected with the pressure chamber. The interactions among the applied electric fields, the piezo ceramic structure, the high viscosity ink, and the pressure chamber structure represent a complex coupling between several areas of engineering. Coupled field analyses are required to take into account these interactions.

This paper investigates the operation of a shear mode piezoelectric transducer using direct coupled field finite element analysis. It is shown that the coupled field analysis method is an effective way to understand the underlying physics of shear mode piezoelectric operation and can be used to optimize a printhead design.

Introduction

In various Spectra's shear mode piezo printheads, a single piezoelectric transducer is used to drive an array of drop-on-demand ink ejectors[1]. The drive mechanism consists of a piezoelectric material bonded to a jetting module with multiple pressure chambers, forming a moveable wall for each chamber. A series of specially arranged electrodes divide the piezoelectric transducer into discrete, deformable sections, each of them corresponding to an ink ejector. The shear mode motion of the piezoelectric transducer is excited by applying an electric field perpendicular to the transducer's poling field at the desired electrodes, pushing the wall into the pressure chamber or pulling it out. Therefore, the application of a voltage pulse can generate an acoustic pressure wave in the chamber. The propagation of the acoustic pressure wave conveys the pressure to the meniscus in the orifice, resulting in the ejection of a drop. The operation of a piezo printhead involves the coupling between different engineering areas. Piezoelectricity, for example, is the interaction between the structural and electric fields. There is also a strong two way coupling between the ink and the surrounding structure. The inward displacement of piezo material into the pressure chamber compresses the ink and increases the pressure. The rising pressure in the chamber, on the other hand, can have a negative effect on the further displacement of the piezo transducer. To accurately predict the printhead performance, engineering analyses should take into account these interactions.

This paper demonstrates that finite element analysis can be applied to the multiple coupling problems in the shear mode printheads. The numerical modeling method has showed itself to be a substantial tool for the development of complex printheads.

Problem Formulation

The first coupling problem is the piezoelectricity. The shear motion of piezoelectric material is a linear interaction between electrical and mechanical systems. Therefore the coupled field problem can be formulated in terms of the electromechanical constitutive equations[2-3].

$$\begin{bmatrix} T \\ D \end{bmatrix} = \begin{bmatrix} c & e \\ e^T & -\varepsilon \end{bmatrix} \begin{bmatrix} S \\ -E \end{bmatrix} \qquad (1)$$

where T, D, S, E are stress, electric flux density, strain, and electric field vectors; c, e, and ε are elasticity, piezoelectric and dielectric matrices. Equation (1) indicates that the structural and electric fields are coupled by piezoelectric matrix e, which relates the electric field vector E to the stress vector T. It has been shown that the finite element formulation of equation (1) can be expressed in the same form as the classic equation of structural dynamics[2].

Another coupling problem encountered in a piezo printhead is the fluid-structure coupling. Ink in a printhead constantly interacts with the piezo transducer, the walls of pressure chamber, and the orifice plate. At the interfaces between ink and its surrounding structure, the equation for structural dynamics should be considered along with the Navier-Stokes equations of fluid momentum and the flow continuity equation. Since the mean flow of the ink in a printhead is very low and the mean density and pressure may be assumed uniform under the given operating conditions, the governing equation can be simplified to the acoustic wave equation[4]. The discretized wave equation and the transient structural dynamic equation for one element may take the following form:

$$\begin{bmatrix} M^s & 0 \\ M^{fs} & M^f \end{bmatrix} \begin{bmatrix} \ddot{U} \\ \ddot{P} \end{bmatrix} + \begin{bmatrix} C^s & 0 \\ 0 & C^f \end{bmatrix} \begin{bmatrix} \dot{U} \\ \dot{P} \end{bmatrix} + \begin{bmatrix} K^s & K^{fs} \\ 0 & K^s \end{bmatrix} \begin{bmatrix} U \\ P \end{bmatrix} = \begin{bmatrix} F \\ 0 \end{bmatrix} \quad (2)$$

where M, C and K are the mass, damping and stiffness matrices respectively. The superscripts s, f and fs indicate if it is a structural, fluid, or the fluid-structure coupling matrix. U, P and F are structural displacement, fluid pressure and structural load vectors respectively. A dot above a variable denotes a time derivative.

In a direct coupling finite element analysis, special types of elements should be used to embody all necessary degrees of freedom in the problem. Some engineering software developers have made great efforts to provide various elements in their products for the coupled field analysis. Spectra has successfully used ANSYS® /Multiphysics in the printhead development. ANSYS® has a wide range of coupled field analysis capability[5], which includes the coupling phenomena described by equations (1) and (2). In addition, advances in computer architecture have made it feasible to apply the computational paradigm to a complex printhead system. We have performed three dimensional transient dynamic analyses using the 64bit version software on Silicon Graphics' Indigo 2 workstation.

Results of Simulation and Discussions

Shear motion in a piezoelectric medium is accompanied by an electric field through piezoelectric coupling. The pattern of the electric field is mainly determined by the arrangement of electrodes, which have a significant impact on the printhead performance. The field strength also depends on the properties of piezo material and the applied voltage. To achieve highly efficient shear motion, a good design should maximize the field strength perpendicular to the poling filed with minimum voltage load. Figure 1 shows the calculated electric field distribution in the piezo transducer for a given design similar to the shear mode transducer for an ink jet systems described by Fischbeck[1]. This figure is a cross-sectional view of a half pressure chamber. The top plate is the piezoelectric transducer, which is previously poled from the bottom to the top in the thickness direction. Electrodes are placed on the surfaces of the piezo transducer. Below the piezo plate are an ink pressure chamber and supporting array body. As we expect, the applied voltage on the electrodes creates the desired electric field pattern that can excite the shear mode motion of the transducer. Carefully analyzing the field patterns under different designs can uncover the influences of many design parameters. We have investigated various important variables to achieve efficient designs for our products[6].

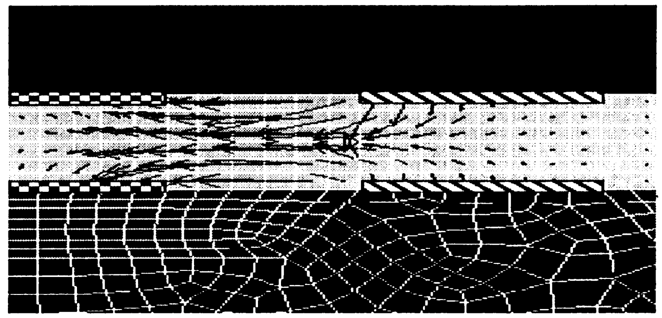

Figure 1: The electric field distribution in a shear mode piezo printhead.

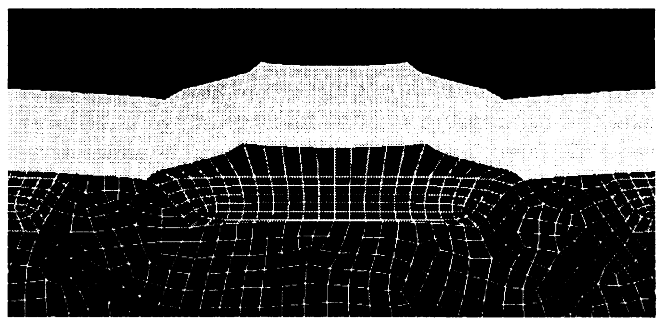

Figure 2: The displacement of piezo transducer calculated using coupled field finite element analysis.

The piezoelectric plate shears when the electric field vector is perpendicular to the polarization vector, causing the piezoelectric plate in the vicinity of the central electrodes to deflect in the direction parallel to polarization direction. Figure 2 illustrates the displacement of the piezo transducer when a negative voltage pulse is applied. Changing the polarity of the applied voltage moves the plate in the opposite direction. Therefore the movement of a piezo transducer can be precisely controlled by a properly designed voltage pulse. As a result, a predictable pressure pulse can be generated by the action of the piezoelectric transducer because it forms one of walls of the pressure chamber. It should be noted that, in order to make the subtle changes visible, the displacement of the piezo plate is exaggerated in these figures. The actual displacement is on the order of several tens to several hundreds of Angstroms, depending on the material properties, the electrode pattern and the applied voltage.

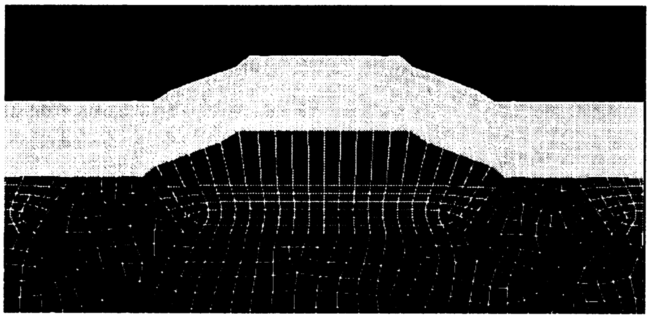

Figure 3: The displacement of piezo transducer calculated without using ink-structure coupling.

Figure 3 shows the displacement of the same model calculated without considering the coupling effect between the ink and the surrounding structure. For easy comparison, the image keeps the same display magnification as that of Figure 2. The supporting structure looks much stiffer even though all material properties in the model are kept unchanged. The maximum displacement is found to be nearly twice that of the coupled case. Accordingly the volume displacement would be much larger. This problem is clearly caused by ignoring the coupling effect. The pressure generated in the ink should have an impact on its surrounding structure. Lifting the roof of the pressure chamber creates a negative pressure inside, which, in turn, will prevent the roof from moving further up due to the pressure differences at the two sides of the transducer. It is clear from this example that this two-way coupling case is best evaluated using coupled field analysis.

Materials used in a particular printhead design should meet certain criteria. For instance, the supporting array body should have a certain stiffness because any source of compliance in the printhead can absorb the acoustic energy, directly affecting the jet performance. On the other hand, a very rigid design may have some other undesirable aspects. Whether a candidate material can function well under the required operating environment can be closely examined by coupled field analysis. In Figure 2, the compliance of the supporting material can be easily identified. Many other important material issues can be addressed in a similar way. The effects of any particular variable on jet performance can then be quickly determined.

Coupled field analysis is not only useful for design purposes, but also helpful in finding the potential problems in manufacturing processes. As an example, it can be used to analyze the transducer's registration problem. The misalignment of a piezoelectric transducer to the pressure chamber can affect the printhead performance, causing a significant drop in jet velocity. This problem can be studied using the finite element model. Figure 4 shows a skewed shear mode displacement due to the misalignment error. It is found that the pressure in the chamber is substantially lower than that in Figure 2. Further analysis indicates that pressure is inversely proportional to the degree of misalignment. Accordingly jet velocity decreases in a similar manner. In this case, numerical modeling is not only used to suggest important scenarios and results, but also provide solutions to correct the problem. A new design that can make the piezo transducer less sensitive to misalignment error has been found through an intensive search. It has been proved that the new design indeed works as predicted. Hence the uniformity of jet velocity is greatly improved.

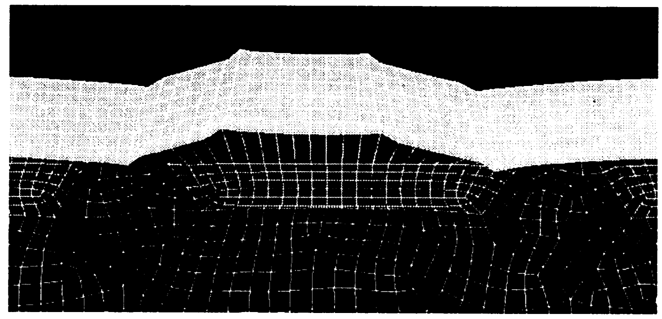

Figure 4: The displacement of a misaligned piezo transducer.

Three dimensional transient dynamic coupled field analysis is particularly useful for the study of acoustic pressure wave propagation phenomena. An acoustic reflection occurs at every impedance mismatch interface. There are many geometrical and material mismatches in a complex printhead. They are the sources of acoustic wave reflections. A good design can effectively harness some of reflections to maximize the use of the pressure initially generated in the chamber. Meanwhile, it should eliminate the undesirable acoustic reflections quickly. We have successfully used the coupled field analysis technique to trace the acoustic waves as a function of time in various regions in a printhead. These studies not only improve our understandings of the insight of a piezo printhead, but also help us to develop better products.

Coupled field analysis can be found useful in many places. It has been successfully used to improve the jet frequency response, minimize the jet to jet crosstalk, and determine the effects of various design and manufacturing variables on the performance of the printhead. Numerical analysis also demonstrates its economical benefits. A lot of time and cost for the evaluation of prototypes can be saved. It helps to develop high performance printheads quickly and economically.

Summary

Coupled field finite element analysis is an invaluable tool to accurately evaluate the operation of a shear mode piezoelectric printhead. There are many application areas in which the numerical solutions play important roles. We are now approaching the level of geometric and physical complexity that may yield solutions to scenarios physically realistic enough to provide practical results for the further development of shear mode piezoelectric printheads.

References

1. K. H. Fischbeck and A. T. Wright, US patent No. 4,584,590, (1986).
2. H. Allik and T. J. R. Hughes, International Journal for numerical methods in engineering, Vol. 2, 151-157 (1970).
3. T. Ikeda, Fundamentals of Piezoelectricity, (1996).
4. L. E. Kinsler, A. R. Frey, A. B. Coppens and J. V. Sanders, Fundamentals of Acoustics, (1980).
5. P. Kohnke, ANSYS® Theory Reference, (1997)
6. Y. Zhou, Internal Memo, Spectra Inc., (1996).