

# Animation of Traveling Electrostatic Waves on Personal Computers

GRAHAM S. WRIGHT AND JOSEPH M. CROWLEY, SENIOR MEMBER, IEEE

**Abstract**—The traveling-wave electric fields needed in electrohydrodynamic induction pumps are normally produced by multiphase voltages applied to discrete electrodes which line the walls of the flow channel. Because both the voltages and the electrodes are discrete, the actual fields differ considerably from the ideal sinusoid that is often assumed in the theory. This discrepancy may weaken the pumping force and also reduce the allowed voltage levels by encouraging breakdown. To give a better picture of the actual fields in the pump, a computer animation of the wave was prepared on a personal computer. This involved 1) a finite difference solution for the potential, using spreadsheet techniques; 2) translation of this solution for different voltage phases and active electrodes; 3) superposition of all fields at a given time, producing a plot of the field along the wave direction, which is a single frame in the movie; 4) sequencing the frames, using inexpensive commercial software.

## INTRODUCTION

TRAVELING electrostatic waves are used in pumping insulating liquids [6] and in conveying particles through gases [4]. The devices based on these waves are often analyzed under the assumption that the waveform is a pure sinusoid, but in practice the traveling wave is usually implemented by constructing a large number of electrodes, each driven by a separate voltage source with a controlled phase relation to the adjacent electrode. Early versions of these devices have used over 20 different voltage phases, which gives a very smooth approximation but also requires complex wiring arrangements. Later devices [7] have reduced the number of separate phases to three, the minimum required for a traveling wave, but the resulting wave is a poorer approximation to the sinusoid, since it contains many harmonics.

These complex waveforms degrade the performance of the pump in several ways. The higher harmonics produce their own traveling waves, some of which may move in the opposite direction from the fundamental wave, negating its pumping action [3]. The higher harmonics are associated with steeper field gradients, which can cause localized electrical breakdown, especially near the electrodes. This breakdown limits the allowed voltage, and hence the power of the pump. Finally, the higher harmonics draw current from the power supply, which must therefore be larger and more expensive.

Paper IUSD 86-102, approved by the Electrostatic Processes Committee of the IEEE Industry Applications Society for presentation at the 1986 Industry Applications Society Annual Meeting, Denver, CO, September 28–October 2. This work supported in part by the National Science Foundation under grant CBT 85-11596. Manuscript released for publication March 16, 1988.

G. S. Wright is with the Department of Electrical Engineering, 155 EEB, 1406 Green Street, Urbana, IL 61801.

J. S. Crowley is with Electrostatic Applications, 16525 Jackson Oaks Drive, Morgan Hill, CA 95037.

IEEE Log Number 8822917.

There are several methods available to study the nonideal nature of these traveling waves, such as harmonic decomposition [3], charge images [5], and finite difference solutions of the field equations [2]. The results of these analyses, however, are usually difficult to visualize, because the traveling wave changes shape as it moves along the electrodes.

In the past, visualization of complex fields has been achieved by computer animation, in which field solutions at slightly different times are sequenced frame by frame into a computer movie, which can then be projected to display the development of the process. While these films are always useful in gaining insight into complex processes, and are often entertaining, they have rarely been produced outside of large dedicated laboratories because, until now, they required large and expensive equipment.

The basic requirements for a computer movie are

- 1) transfer of the output of the field analysis program to a graphical image, and
- 2) sequencing of successive images.

While not essential, a method for viewing the movie directly on the computer screen is extremely helpful. Without it the movie must be built up frame by frame from screen images, and can only be viewed after a turnaround time, which can be minutes when using video recorders, or days when using film.

Because fast graphical output requires a dedicated computer, it is rarely worthwhile to attempt computer animation while time sharing a mainframe computer. The only other type of computer normally available to an individual whose main business is not computing is a personal computer. Until recently, personal computers have had neither the fast graphical interfaces nor the easy data exchange that would make computer movies simple enough to serve as a design tool rather than a major project.

The latest generation of personal computers, however, provides both of these requirements. Numerical data generated by a field analysis program can be automatically displayed as a graph, which is redrawn each time the input is changed. The graphical image can be copied and "pasted" into an animation program, forming a single frame of a computer movie. The movie can be replayed on the computer screen using variable speed, single frame, reverse, and other features normally associated with film analysis. All of this can be done with standard and relatively inexpensive software, so the individual can concentrate on the design rather than the programming. This procedure is illustrated in the present paper using a

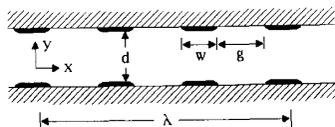


Fig. 1. Typical EHD pumping channel.

Macintosh<sup>™1</sup> computer, with a spreadsheet program (Excel<sup>™2</sup>) to calculate and plot the fields and an animation program (Videoworks<sup>™3</sup>) to construct the movie.

DESCRIPTION OF THE TRAVELING WAVE

Fig. 1 shows a cross section of a typical electrohydrodynamic (EHD) traveling wave pump with electrodes on the sidewalls. The electrode width is  $w$ , the interelectrode gap is  $g$ , and the channel depth (between electrodes) is  $d$ .

The wavelength in this case spans three pairs of opposing electrodes. Each pair is connected to a different phase of a balanced three-phase voltage source. Three phases is the minimum that gives the traveling wave a preferred direction, and so is simplest to implement. Six-phase arrangements have also been analyzed and will be discussed later.

The channel is considered to be wide compared to its depth and wavelength, so a two-dimensional solution for the fields is appropriate. The potential is symmetric about the channel centerline and periodic along the channel, with a period equal to the wavelength. The walls of the channel, which support the electrodes, are normally constructed of good insulators, with a dielectric constant close to that of the liquid being pumped. In the results presented here, the dielectric constants of the fluid and wall are assumed to be equal.

The electric potential surrounding the electrodes was computed with a finite difference method implemented on a spreadsheet program, as described in an earlier work [1]. This is an exterior, or open-boundary problem in which the field is nonzero throughout all space and is not strictly confined to some finite region. The finite difference method requires that the outer boundary be placed at a finite distance from the electrodes, introducing a source of error. We know from the analytic solution of the pure sinusoidal traveling wave that the potential approaches zero exponentially with a decay length  $\lambda/2\pi$  for the fundamental, and less for the higher harmonics. We can therefore truncate our grid to a height of about  $\lambda$  without incurring an error of more than  $e^{-6} \approx 0.25$  percent. The voltage at this outer boundary is not given in advance, but it is often assumed to be equal to the average of the electrode voltages, or else to zero. Both choices were tried without changing the average electric field at a given position in the channel by more than 1 percent.

A grid large enough to extend out for a wavelength, and at the same time fine enough to give the details of the field near the electrodes, cannot be conveniently implemented on a small computer, so a windowing technique [1] was used. There were three successive grids, with the first covering the entire region

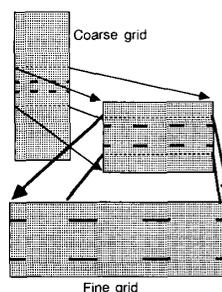


Fig. 2. Typical two-stage windowing with 2:1 magnification.

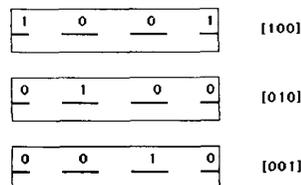


Fig. 3. Schematic of half-channel grids of three basis functions, showing electrode potentials.

and the last restricted to the region near the electrodes and in the channel, as shown in Fig. 2.

The electrode voltages are time-varying, and we would like to know how the  $E$  field varies over the course of a cycle. It might seem, then, that we must put in different electrode voltages and reconverge the spreadsheet for many different times in order to study time variation. But in fact, the principle of superposition makes it possible to study continuous time variation with no reconverging. There are three electrodes in each wavelength, each of which can be independently excited. This gives rise to three basis functions, each of which has one of the electrodes at 1 V and the other two at 0 V (Fig. 3). The total solution is a linear combination of these basis functions with time harmonic weights corresponding to the phase of the excitation (Fig. 4).

There is yet another symmetry in the problem which reduces the computational effort by about a factor of 3. Any of the basis functions can be obtained just by translating the first one by  $\pm 1/3$  period, so the potential field set up by any electrode can be calculated by shifting the solution of the first one, which is the only one requiring a numerical field solution. Thus we can find the potential in the channel at any time, with any combination of electrode voltages, by weighting and shifting a single converged grid.

ANIMATION OF THE SOLUTION

Once the single grid has been converged, the potential for any instant of time can be calculated by multiplying the basis solution by the instantaneous voltage applied to each electrode. The computer screen during this operation (Fig. 5) displays both the entry form for the phase angle information and the graph of potential along the channel at a particular depth. Whenever the phase angle is changed by typing in a new value, the graph is automatically updated to display the new potential distribution. This graphical output is very useful but could not

<sup>1</sup> Registered trademark of Apple Computer.  
<sup>2</sup> Registered trademark of Microsoft Corporation.  
<sup>3</sup> Registered trademark of Haydon Software.

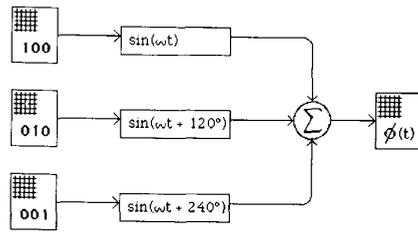


Fig. 4. Potential is sum of (time independent) basis functions scaled by time-varying coefficients.

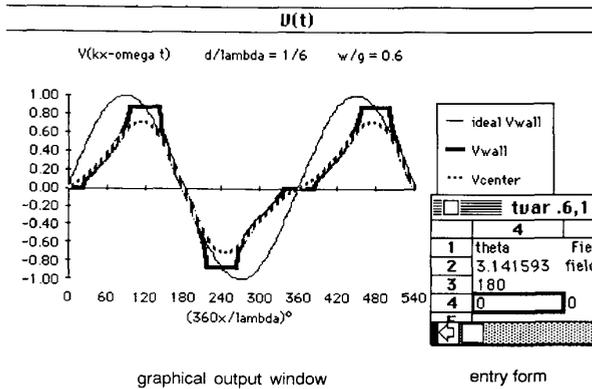


Fig. 5. Screen display during field calculation.

be considered animation because several seconds are required to recalculate the field and update the graph. It is possible to save each graphical image in a "scrapbook," however, for later use in an animation program.

Once the images for all the desired times in a cycle of operation have been saved, they are copied into a second program, which provides the animation. In the program used here (Videoworks), each graph becomes a "castmember" that can be placed on the computer screen for any desired frame, in any desired place. The simplest procedure is to place each graph on the screen for a single frame, replacing it with the next graph in exactly the same spot. When the animation is run, the axes and labels appear to stay in the same place while the curve that represents the potential appears to travel downstream, changing shape as it goes.

A single frame of such a movie is shown in Fig. 6. The graph shows the potential along the plane of the electrode for a six-phase pump. The potential is constant at each electrode, and nonuniform in between. The slope of the curve gives the electric field strength, which is useful in predicting breakdown, and is also related to the pressure developed by the pump.

At the top of Fig. 6 is the "control panel" of the animation program, which allows the wave motion to be analyzed in more detail. The replay can be stopped at any point by the stop button, restarted from that point by the play button, or rewound to the first frame by the rewind button. The speed of the replay can be adjusted by the speed control, which gives nominal speeds from three frames/s to 60 frames/s. The replay can also be stepped forward or backward, one frame at a time,

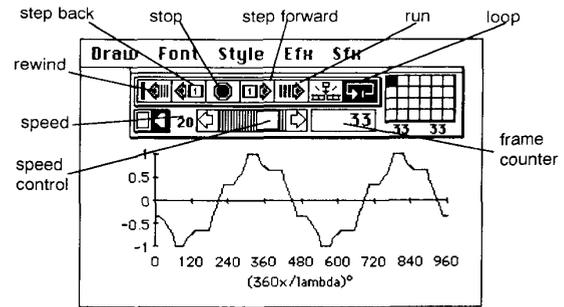


Fig. 6. Single frame in six-phase traveling-wave movie, along with control panel.

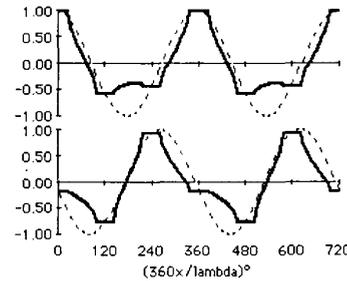


Fig. 7. Animated graphs with two different waves.

by the step buttons, or can be left to repeat indefinitely by the loop button.

Although the nominal speed of the replay can be set as high as 60 frames/s, the actual speed is usually limited by the time needed to redraw the image. This time increases with the size of the image, so it is best to keep the image as small as possible if high speeds are needed. As an example, the image shown in Fig. 6 ran at an effective speed of 14 frames/s, which is sufficient to give smooth animation. Removing the control panel from the display increase the projection rate to 20 frames/s while doubling the area of the image cut the speed by a factor of 2.

Multiple graphs can be combined in the same frame (Fig. 7) to compare different types of operation of the pump. In Fig. 7, two separate frequencies are used to excite a three-phase pump, and the traveling waves for each case are displayed on two separate graphs. The ideal traveling wave is also shown as the dotted line on each graph, for comparison. The control panel and menu bar have been removed from view, which gives a less cluttered appearance and faster animation.

#### DISCUSSION

The movies described here were prepared by copying each image from the electrostatic field program into a "scrapbook" and then rerunning the program to get the next image. After all the desired images were collected, the animation program was run, and each image copied from the scrapbook. With a long movie, the transfer process can take some time. Fortunately there are several alternative approaches to image transfer that require less human intervention. Both programs can be run while being kept active (using a program called the

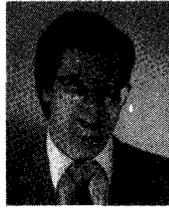
Switcher™<sup>4</sup> so that the images can be immediately transferred from the spreadsheet to the animator. This requires more memory, but eliminates the intermediate scrapbook. A second approach relies on the use of macro commands, which can copy the sequence of commands needed to increment the time, update the graph, copy it, transfer it to the automation program, insert the new frame, and loop back to the spreadsheet program. This completely automates the filmmaking process once the first transfer has been accomplished.

The techniques presented here represent one possible approach to computer animation of fields. One traditional alternative, also available on current personal computers, uses a standard programming language like Basic or Fortran to compute the fields and display the output graphically. This requires less transfer of data from one program to another, but since the field computations must be carried out in sequence with the graphics, the animation is quite slow unless the field computations are relatively straightforward. There is also less flexibility in changing playback speed and direction. On the other hand, this approach makes the effects of changes in the input conditions visible more rapidly than the method described in the present work.

#### REFERENCES

- [1] J. M. Crowley, "Electrostatic fields on PC spreadsheets," *J. Electrostatics*, vol. 19, pp. 137-149, 1987.
- [2] P. T. Krein, "A theoretical study of the thermal electrohydrodynamic induction pump with harmonics and inhomogeneous fluids," *Phys. Fluids*, vol. 27, pp. 315-317, 1984.
- [3] P. T. Krein and J. M. Crowley, "Harmonic effects in electrostatic induction motors," *Elec. Machines Power Syst.*, vol. 10, pp. 479-497, 1985.
- [4] S. Masuda, K. Fujibayashi, and K. Ishida, "Elektrodynamisches Verhalten aufgeladener Aerosolteilchen im inhomogenen Wechselfeld und seine Anwendungsmöglichkeiten in der Staubtechnik," *Staub-Reinhalt. Luft*, vol. 30, pp. 449ff., 1970.
- [5] S. Masuda and T. Kamimura, "Approximate methods for calculating a non-uniform traveling field," *J. Electrostatics*, vol. 1, pp. 351-370, 1975.
- [6] J. R. Melcher, "Traveling-wave induced electroconvection," *Phys. Fluids*, vol. 9, pp. 1548-1555, 1966.
- [7] J. Seyed-Yagoobi *et al.*, "Induction electrohydrodynamic pump in a vertical configuration," in *Conf. Record of 1985 IEEE-IAS Annual Meeting*, Toronto, ON, Canada, Oct. 6-11, pp. 1567-1579.

<sup>4</sup> Registered trademark of Apple Computer.



**Graham S. Wright** was born December 12, 1961, in Madison, WI. He received the B.S. degree from Washington University, St. Louis, MO, and the M.S. degree from the University of Illinois, Urbana, in 1984 and 1987, respectively, both in electrical engineering. He is currently a Ph.D. candidate in electrical engineering at the University of Illinois, working on the electrohydrodynamics of a fluid meniscus with application to ink jet printing.



**Joseph M. Crowley** (M'78-SM'78) was born in Philadelphia, PA, in 1940. He received the B.S., M.S., and Ph.D. degrees from the Massachusetts Institute of Technology, Cambridge, in 1962, 1963, and 1965, respectively, all in electrical engineering. He then studied fluid mechanics at the Max Planck Institute in Göttingen, Germany, as a NATO Fellow.

In 1966 he joined the faculty of the University of Illinois, where he is currently Professor of Electrical and Computer Engineering and Professor of Mechanical and Industrial Engineering. He teaches primarily in the areas of electromechanics and electromagnetism but has also taught most of the required electrical engineering courses during his tenure. His attention to undergraduate instruction has led to regular citation in the *List of Excellent Instructors*, based on student evaluations conducted by the University. He also serves as Director of the Applied Electrostatics Laboratory, supervising research in areas such as electrohydrodynamic pumping and electrostatic discharge protection. Much of this work has been published in the form of numerous articles, several patents, and a book, *Fundamentals of Applied Electrostatics*. He has consulted extensively in areas involving electrostatics and fluid mechanics, especially in printing and copying processes, under the aegis of his consulting firm, Joseph M. Crowley, Inc. He is currently on leave from the University of Illinois to serve as President of Electrostatic Applications, Morgan Hill, CA.

Dr. Crowley is a member of Sigma Xi, Tau Beta Pi, Eta Kappa Nu, the SPSE, the SID, the APS, and the EOS/ESD Association, as well as Electrostatics Society of America. He is listed in numerous honorary directories, including *Who's Who in America* and *Who's Who in Engineering*.