Demonstrating principles of physical optics through interactive computer simulations

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ABSTRACT

Interactive simulations have been developed illustrating basic principles of physical optics in three major areas: 1) electric field behavior in various polarization states, 2) propagation of traveling plane waves through birefringent and optically-active media, and 3) Fresnel diffraction and its relationship to and interpretation with Cornu's spiral. All of these areas emphasize the wave nature of light as expressed by an oscillating electric field. These simulations make use of high-resolution (VGA) color animation in a PC/MS-DOS environment; this enhances the presentation and appeal of these simulations to students. These simulations are presently being used by 1) physics majors in an upper-level applied optics course and 2) lower-level honor students who are being introduced to research projects in physical optics. The success of these programs as a vehicle for imparting a conceptual understanding of the physical principles involved will be presented.

1. INTRODUCTION

Computer programs that demonstrate various facets of optical physics are not new.[1,2,3] While both ray and wave optics programs have been presented, few of them have included high resolution video animation techniques (see, however, Ruiz[3]). With the recent increase in availability of high resolution video adapters and high speed personal computers, the possibility of exploiting basic animation techniques for a general audience has become feasible.[4] Although several languages are readily available to the personal computer community, it was decided that a modern dialect of BASIC, PowerBASIC (SPECTRA Publishing, 1030 D East Duane Ave., Sunnyvale, CA 94086), represented a good "general purpose" language for this project. Since no really "esoteric" programming techniques were used for this project, the BASIC code can be rewritten in other languages with little effort - in fact, C versions of several of these programs have been written.

This paper will describe five programs that have been used for student instruction/demonstration in a senior-level physical optics course taught at Murray State University. These programs fall into two basic areas - Fresnel diffraction and traveling plane wave propagation. The Fresnel diffraction programs include an animation of the Cornu spiral method applied to a single slit, and two complementary programs that plot the Fresnel diffraction pattern for a

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single slit and for a single stop. The traveling wave programs, all of which are animated, include harmonic plane waves with adjustable parameters (direction of travel, variation in either space or time, relative component phases) propagating in an isotropic medium, in an optically active medium, and in a birefringent medium.

These programs will be discussed in the following sections. The first section will discuss the programming techniques used in each demonstration. The second section will discuss the interactive features of each program and its effectiveness as a teaching tool.

2. PROGRAM DESIGN

2.1. Fresnel diffraction demonstrations

Fresnel diffraction integrals, and their graphical representation via the Cornu spiral, are standard topics in introductory optics texts.[5,6,7] It was desired to illustrate the use of the Cornu spiral with a computer animation. In order to run fast enough for a "real time" animation, the Cornu spiral is represented by up to 4000 points which are precalculated and stored in an array. Since this precalculation of points would be very time consuming if an actual numerical integration of the Fresnel integrals were performed, rational polynomial approximations are used for these integrals.[8,9] This results in only a few-second wait on a standard 12 MHz AT class personal computer equipped with a numeric coprocessor.

The actual animation is accomplished using one of two methods, depending on the programming language. For the BASIC code, a line segment connecting the points on the spiral corresponding to the end points of the Fresnel integration is drawn and left on the screen long enough for the viewer to register its presence. This line is then erased and redrawn for the next pair of integration end points. The viewer perceives this draw-erase-redraw sequence as a smoothly moving line sliding along the spiral. For the C code, more sophisticated graphics commands are available and it is not necessary to actually erase the line. Rather, the line is drawn twice in an exclusive OR (XOR) mode; the second draw then "erases" the original line. This method has the advantage that background features (such as the axes) are not erased by the line draws, resulting in a more visually-satisfying screen. In order to minimize "flicker", the draw-erase sequence is synchronized to the vertical retrace of the video display.[10] As this animation is in progress, the resulting diffraction intensity profile is drawn in the lower quadrant of the screen. The dimensions of the diffraction pattern graph are user selectable, as is the slit dimension.

The animated Cornu spiral only devotes a quarter of the screen to the diffraction pattern. As this limits the resolvable detail, two additional programs that display a full-screen diffraction pattern were written. The calculational method is the same as the above. One of the programs displays the same pattern as the animated program (i.e., the diffraction pattern for a single slit). The second program displays the complimentary diffraction pattern (i.e., the diffraction pattern for a wire).

2.2. Traveling wave demonstrations

The animation of the electric field vector of a traveling wave is accomplished in BASIC using the above "draw-erase-redraw" technique. Two separate sum indices are maintained, one for the spatial variation and one for the temporal variation of the wave argument. Several "hot keys" are supported for changing various parameters of the animation. For example, the sign of one of the above index sums can be changed, providing a view of the wave traveling either toward or away from the viewer. Various initial states of polarization are possible by specifying initial amplitudes and phases for the components of the wave; then, by incrementing/decrementing the relative phase, one can observe how the various polarization states depend on the relative phase. To better visualize the envelope of the polarization state, a "trace" mode can be entered in which the tip of the electric vector leaves a trail of dots. Finally, the animation can be paused and advanced stepwise. This mode also highlights the component projections of the electric field.

Two additional programs that emphasize the interaction of polarized light with matter have been developed. The first simulates a plane wave propagating through a birefringent medium. In this case, the relative phase of the wave components is a linear function of the distance of travel in the medium. The simulation allows the user to select either a positive or a negative birefringent medium, and to start/stop the birefringent behavior as desired.

The second program simulates a wave propagating in an optically active medium. In this case, the speed of propagation depends on the sense of the circular polarization of the wave. In this program, a plane polarized wave is represented as a sum of left and right circularly polarized components. All three of these waves - the left circular, right circular, and plane polarized waves - are animated in the simulation. The simulation allows the user to select either a dextro- or levorotatory medium. The user can start/stop the optically active behavior as desired.

3. PROGRAM USAGE

The above programs have been made available to students taking a junior/senior level physical optics course, as well as freshmen and sophomore students associated with an optics research project at Murray State University involving the measurement of Fresnel diffraction patterns for various apertures using CCD detectors.

3.1. Traveling wave programs

The traveling wave program has been useful for introducing the concept of helicity and demonstrating the important role that viewing direction has on its definition. By changing from an incoming to an outgoing wave, the user can directly see the reversal of rotation sense of the electric field vector. This program has also been very useful in the demonstration of polarization states and their relation to amplitude and relative phase angle. By being able to vary the relative phase angle in "real time", the transition between plane polarization, elliptical polarization, and helicity can be easily observed and studied.

Once a through understanding of wave propagation and polarization states has been obtained, students can move on to the concepts of birefringence and optical activity. The programs that address these topics allow the students, again in "real time", to observe how polarization depends on location within such media. In particular, it can be clearly seen that optical activity does not change the polarization state, but only rotates the plane of polarization for a linearly polarized wave as it traverses the optically active medium. Once the wave leaves this active medium (the activity is turned off using a hot key), it propagates the same way it did before it entered the active medium, except that the plane of polarization has been rotated. By being able to choose which circular polarization component increases in velocity, students can better understand the concept behind dextro- and levorotatory media.

In contrast to optical activity, birefringent media is seen to affect the polarization state of wave propagation. In particular, by turning birefringent behavior on and off at the proper times, the student can, for example, follow a plane wave through a birefringent medium and see a plane polarization state converted into a circular polarization state. By monitoring the relative phase at the start and at the end, the student can see that a relative change of 90 degrees is required to change from a wave plane-polarized at 45 degrees to a circularly-polarized wave; this example provides graphic proof of the action of a quarter-wave plate. Again, the sense of birefringence - positive or negative - can be chosen by the student.

3.2. Cornu programs

The Cornu's spiral animation program has been found to be very useful to students as a conceptual, as well as a practical, tool. By observing, in the single-step mode, the movement of the "slit" along the spiral, students are better able to understand the meaning of the integration limits used in Fresnel integration. This program also proves useful in bringing out the detail of the diffraction pattern and, therefore, in showing the importance of using a small step size when plotting a Fresnel diffraction pattern. By a proper choice of geometry, the transition from Fraunhofer diffraction to Fresnel diffraction can be followed in as much detail as desired. An additional "bonus" often provided by this program results from a commonly asked student question: "How did you do the integrations so fast?" This provides an excellent opportunity for introducing rational polynomial approximations and Pade approximant concepts.[9,11]

Following the conceptual understanding provided by the above animation program, students explore the concepts of complementary screens in two additional programs. One program plots the Fresnel diffraction for a slit (as in the animation program), while the other plots the pattern for a narrow obstacle, or wire. These programs introduce the students to Babinet's principle and allows them to observe its function in Fresnel diffraction, where the complimentary screens do not generate equivalent irradiance patterns. The slit program also allows the student to approximate the semi-infinite opaque screen and observe that the irradiance at the geometric edge is 25% of the unobstructed irradiance. Finally, these programs can also serve as a research tool since, by varying the geometric parameters, one can reproduce a diffraction pattern measured, for example, with a CCD.

4. CONCLUSION

Student feedback has indicated that the programs presented above have achieved their purpose, namely, to present basic principles in two areas of physical optics in the form of interactive computer simulations using high resolution video display and animation. These programs can be easily modified to support new, higher resolution video standards as they become readily available (for example, the new IBM XGA video adapter, which supports 256-colors at a resolution of 1024x768 pixels). These programs have been demonstrated in optics workshops sponsored by the Murray State University Department of Physics, and are available for use by regional high school physics instructors. Anyone interested in obtaining copies of these programs should contact the authors.

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