Introductory physics of harmonic distortion in fluorescent lamps

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Although the use of fluorescent lamps has been increasing due to their energy-saving advantages, discussions about them are rarely found in introductory physics texts. Although most of the disadvantages of fluorescent lamps have begun to be remedied, there still exist some problems that need to be solved. Two of the problems involve buzz and high-frequency flicker generated by some ballasts. In analogy with acoustic instruments, we summarize some of the causes of such higher harmonics and suggest that further study of the phenomena is warranted to minimize the problems and to successfully implement wide-scale commercial and residential use.

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I. INTRODUCTION

Recently, there has been a surge of articles on the fundamentals of LED's and incandescent lamps at the introductory physics level.[1–5] However, there has not been a comparable discussion of fluorescent lamps, even though they are being used more commonly around the world to replace conventional incandescent fixtures in both commercial and residential applications. Their many advantages over incandescent lamps have spurred their popularity, while some of their disadvantages have driven investigators to find ways to improve the lamps. Certain important aspects of the behavior of these lamps are still unfamiliar to the broad scientific readership and merit further discussion. For example, Bloomfield's textbook[6] provides an in-depth look at fluorescent lamps, but lacks an updated discussion of the effect of higher harmonics, which constitutes a major problem.[7–9]

Incandescent lamps produce light by heating a filament until it glows white hot, a process called incandescence. Fluorescent lamps use a discharge of electric current to excite mercury atoms in neon, argon, and/or krypton gas, whose electrons then give off energy (about 1 in every 1000 gas atoms inside the tube is a mercury atom), a process called luminescence.[6] The energy emitted by the mercury atoms in the gas is often in the form of ultraviolet light, so a phosphor coating on the inside of the lamp transforms the ultraviolet to visible light, a process called fluorescence. The role of the ballast in the lamp is to start this discharge (by heating the electrodes or by applying a high voltage) and to regulate the inherently unstable current through the tube.

The advantages of fluorescent lamps over incandescent lamps are many. First of all, they are 2–4 times more efficient: while most of the power consumed by incandescent lamps is wasted as invisible infrared light (excessive heat production),[1] fluorescent lamps produce much more visible light with the same amount of electrical power.[6–9] In addition, fluorescent lamps have much longer lamp life than incandescent lamps: 10 000–20 000 hours versus 1000 hours.[7]

Fluorescent lamps, however, present several disadvantages not present in incandescent lamps. First, they must be properly disposed or recycled to keep all of the mercury out of the environment. In addition, turning the lamps on and off frequently wears out their electrodes thereby reducing the lamp life. This reduction is due to the fact that mercury ions collide with the electrodes and chip away their tungsten atoms, a process called sputtering, which is most severe when starting a preheat fixture. Physically, fluorescent lamps are larger, their color may sometimes be cooler and less pleasing than a warm incandescent lamp color, and their elongated shapes may produce suboptimal lighting patterns.[7] Although many of these issues have been solved by new model designs, the generation of higher harmonics by the ballast in fluorescent lamps remains only partially understood and thus requires further study. Lamps with excessive higher-harmonic distortions exhibit reduced light power intensity, additional lamp flickering, and compatibility problems with other devices connected to the electrical network or operating nearby. Furthermore, the potential for adverse effects in a building depends on the size of the load imposed by harmonic-generating lamps as a proportion of the total building load.

II. HIGHER-HARMONIC GENERATION IN FLUORESCENT LAMPS

Even though electric power systems are designed to provide users with pure and stable sinusoidal voltages, the levels of harmonic distortions of voltage and current waveforms in power systems have steadily increased due to the incessantly growing demand for electricity.[7] Harmonic distortions affect sensitive equipment connected to the power networks and are especially problematic for compact fluorescent lamps. Recent tests indicate that the harmonic distortions due to power systems are compounded by the generation of higher harmonics by fluorescent lamps. In what follows, we address the higher harmonics generated in these lamps. These harmonics depend significantly on the type of ballast used (electromagnetic or electronic) and directly affect the lamp's light output.[7,9] Temperature also has an effect on the lamp's light output, especially the time to luminous equilibrium.

A brief analogy between fluorescent lamps and acoustic instruments illustrates how higher harmonics in the sinusoidal input voltage can generate further higher harmonics in the lamps. Typical frequency spectra of a clarinet and a fluorescent lamp are shown in Figs. 1 and 2. In Fig. 1, the relative (to the fundamental) sound intensity for a clarinet is plotted versus the corresponding harmonics;[10] the first and 25th harmonics correspond to 148.5 Hz (D_3 note) and 3712.5 Hz, respectively. In Fig. 2, the relative (to the fundamental) voltage intensity of a fluorescent lamp is plotted ver-

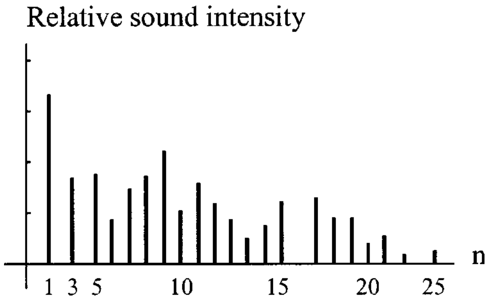

Fig. 1. The relative (to the fundamental) sound intensity for a clarinet is plotted versus the corresponding harmonics; the first and 25th harmonics correspond to 148.5 Hz (D3 note) and 3712.5 Hz, respectively.

sus the corresponding harmonics;[7] the first and 50th harmonics correspond to 60 Hz and 3000 Hz, respectively.

Despite the noticeable differences in their frequency spectra, fluorescent lamps and clarinets have some related physical characteristics. For example, both the ballast of a fluorescent lamp and the reed of a clarinet are designed to start, control, and reduce the generation of harmonics in their respective devices. They also are designed as coupling mechanisms for correct impedance matching. When a simple bell is added to an ordinary sound tube, the generation of higher frequencies in the sound spectrum is considerably abridged. The addition of the bell squeezes the resonance peaks closer together and permits more efficient sound output at higher frequencies. The analogy with the problem of conveying electrical energy from a source to a fluorescent lamp as effectively as possible is apparent, and correct impedance matching is of enormous practical importance. Accordingly, the fact that Fig. 2 contains a greater number of higher harmonics than Fig. 1 indicates that improvement of ballasts is of paramount priority. Furthermore, nonlinear phenomena in the lamp and clarinet also contribute to the onset and decay of oscillations, the amplitude of the steady state, and the harmonic content of the respective devices.

Because of its relative simplicity, the clarinet has been more extensively studied than any of the other woodwind instruments.[10] A clarinet is essentially an instrument with a cylindrical bore and a single reed (see Fig. 3). The tone of the clarinet, like fluorescent lamps, is rich in harmonics. The reed of a clarinet generates a wide range of frequencies of sound. This generation of complex vibrations in the air column is accomplished by vortices formed along the flow of

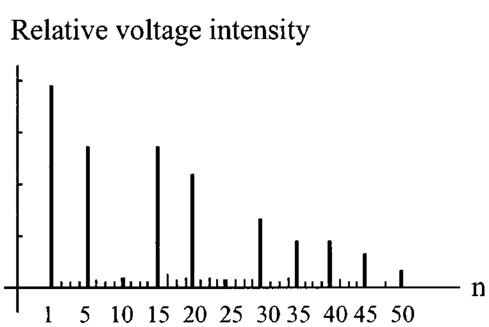

Fig. 2. The relative (to the fundamental) voltage intensity of a fluorescent lamp is plotted versus the corresponding harmonics; the first and 50th harmonics correspond to 60 Hz and 3000 Hz, respectively.

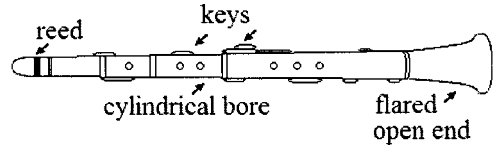

Fig. 3. Schematic of a clarinet.

air in the device. For the case of fluorescent lamps, the electrical current is analogous to the flow of air, and the ballast to the reed, which similarly generates a wide range of nonlinear oscillations.

In general, these nonlinearities and multiple resonances in the device change the output dramatically. The bore of the clarinet, although closely cylindrical over most of its length, differs significantly in the shape of the mouthpiece and in the flaring bell at its foot. Irregularities in the flow of air through the bell have a significant effect on the frequency spectrum, particularly for low notes, and, of course, shape variations near the reed affect the relative frequency of all notes and harmonics.

Similarly, the length and shape of the tube as well as the design of the electrodes have striking effects on the frequency spectrum of fluorescent lamps (see Fig. 4). The behavior of the ballast under different higher-harmonic voltage conditions affects the harmonics produced in the lamp, particularly in the high-frequency range, and consequently the lamp's performance.[7,8] One of the most important aspects of reeds and ballasts is that they are nonlinear, and for nearly all nonlinear systems, the amplitude of the *n*th harmonic depends on the amplitude of the fundamental. Thus, increasing loudness is associated with increasing harmonic development. In the case of fluorescent lamps, harmonic distortion has been consistently measured up to the 50th harmonic.[7]

Another important similarity between the reed and the ballast is the analogous relations between the pressure, P, versus acoustic flow $U(P=ZU)$ and voltage V versus current $I(V=ZI)$, where Z represents the impedance of the reed to the bore of a clarinet and the impedance of the ballast to the tube of a fluorescent lamp. In both cases, the impedance may depend significantly on the amplitude and frequency of operation. As the frequency approaches a resonant frequency, the behavior of the device becomes more complex, as higher harmonics can be generated. The existence of upper and lower thresholds of pressure and voltage outside of which the reed and the ballast are ineffective represents another important feature that the two devices share in common.

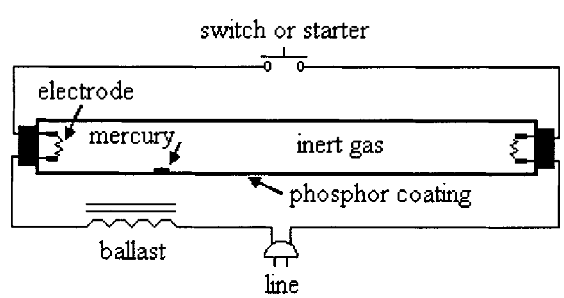

Fig. 4. Schematic of a fluorescent lamp.

III. CONCLUSION

We have addressed some important similarities between fluorescent lamps and clarinets. Although technical engineering papers present an extensive comparative analysis of different fluorescent lamps under a variety of conditions, these papers do not deal with the fundamental physics of higher harmonics generated by the lamps themselves. Besides, discussions about these lamps at the introductory physics level are rarely found in the literature.

The issue of harmonics first surfaced in the 1980s when major utility companies required electronic ballasts to have total harmonic distortion of less that 20% of the fundamental to qualify for the utility's rebate program. However, the levels of harmonic distortions of voltage and current wave forms in power systems have steadily increased due to the growing demand for electricity in recent years. The current needs to be regulated by the ballast in order to supply the right amount of power needed to generate the arc in the lamp. Most test results have indicated that the electrical performance of fluorescent lamps under these circumstances is largely related to the type of ballast used (electromagnetic or electronic).[7–9]

The analogy in this paper between acoustics and electricity is designed to shed some light into the problems of the higher harmonics generated in fluorescent lamps and to suggest that further study of the phenomena is warranted to minimize potential problems.

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THE TAPESTRY OF SCIENCE

The great tapestry of science is woven together in a grand and awesome design with the question How? How can the universe end up with a preponderance of positively charged nuclei? How can fluctuations arise to give birth to galaxies? How can the presence of iron atoms be explained? How can hemoglobin come about? The scientific account starts with our present, everyday universe. Detailed observations of the natural world provide the warp of our tapestry, and the theoretical explanations provide the ''how,'' the weft that holds the picture together.

Owen Gingerich, *Let There Be Light: Modern Cosmogony and Biblical Creation*, edited by Roland Mushat Frye (Charles Scribner's Sons, 1983). Reprinted in *The World Treasury of Physics, Astronomy, and Mathematics* (Little, Brown and Company, Boston, MA, 1991), p. 387.