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Effect of mechanical vibrations on light emitting diode luminaires

Jayalakshmi Paladugu

University of Nevada Las Vegas

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EFFECT OF MECHANICAL VIBRATIONS ON LIGHT EMITTING DIODE LUMINAIRES

by

Jayalakshmi Paladugu

Bachelor of Science
Anna University, India
2007

A thesis submitted in partial fulfillment of the requirements for the

Master of Science Degree in Electrical Engineering
Department of Electrical and Computer Engineering
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Effect of Mechanical Vibrations on Light Emitting Diode Luminaires

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December 2009
ABSTRACT

Effect of Mechanical Vibrations on Light Emitting Diode Luminaires

by

Jayalakshmi Paladugu

Dr. Rama Venkat, Examination Committee Chair
Professor of Electrical Engineering
University of Nevada, Las Vegas

In this work, a LED and two types of Compact fluorescent lamps were investigated for the intensity variation due to mechanical vibrations in the range of 0 to 30 HZ. In general, subjecting the lamps to 24-hour vibration affects the total intensity percentage variations of peak intensities after vibrations is in the range of -25 to +15% compared to those of no vibrations for the light emitting diode luminaires. For the case of compact fluorescent lamps (Nuvue) the variations are in range from +10 to +35%, whereas for the Compact fluorescent lamps (Ecosmart) the intensity peaks range from -10 to +10%. Continuous vibration measurements at varying vibrational frequencies (measurements at each frequency for every 10 minutes) show that in the case of LED luminaires, there is no consistency of intensity peaks in case of light emitting diodes, i.e. there is an increase and decrease in intensities, whereas in the case of both compact fluorescent bulbs, there is an increase in intensity at the wavelength of 546.78nm (wavelength of maximum human sensitivity) which reaches a maximum at around 25Hz. Intensity variation effects due to vibration are attributed to the dropping off loose phosphor coatings in the inside wall of the glass enclosures. This effect is more pronounced in CFLs compared to LED luminaires due to the difference in the way the phosphor is coated/sandwiched.
# TABLE OF CONTENTS

**ABSTRACT** .................................................................................................................. III

**LIST OF FIGURES** ......................................................................................................... VI

**LIST OF TABLES** ............................................................................................................. IX

**ACKNOWLEDGEMENTS** .................................................................................................. X

**CHAPTER 1 INTRODUCTION** .......................................................................................... 1

**CHAPTER 2 LITERATURE SURVEY** ................................................................................ 12
  2.1 Incandescent Lighting ................................................................................................. 12
  2.2 Fluorescent Lighting .................................................................................................. 17
  2.3 Light Emitting Diode Based Lighting ....................................................................... 21
    2.3.1 Light Emitting Diode Development .................................................................. 21
    2.3.2 LED Luminaires for Lighting ......................................................................... 23
  2.4 Summary of Various lighting systems ........................................................................ 29
  2.5 Comparing Incandescent, CFL, LED luminaires ...................................................... 30

**CHAPTER 3 EXPERIMENTAL SETUP** ............................................................................ 33
  3.1 Experimental setup .................................................................................................... 33
    3.1.1 Vibration table .................................................................................................. 33
    3.1.2 Maximum Force and Current ratings .................................................................. 35
    3.1.3 Maximum stroke ............................................................................................... 36
    3.1.4 Amplifier .......................................................................................................... 37
    3.1.5 Frequency generator ......................................................................................... 37
  3.2 Lamp fixture and the bulb ......................................................................................... 38
  3.3 Goniometer ................................................................................................................ 40
  3.4 Spectrometer ................................................................................................................ 42
    3.4.1 Spectrometric measurements ........................................................................... 45
    3.4.2 Measurements calibration and Calculations ...................................................... 45

**CHAPTER 4 RESULTS AND DISCUSSION** .................................................................... 48
  4.1 Spectrometric Measurements ..................................................................................... 49
  4.2 LED luminaires measurement ................................................................................... 49
    4.2.1 Intensity Measurements with varying vibrational frequencies ......................... 64
    4.2.2 Summary and discussion on LED luminaires measurements ......................... 65
  4.3 CFL measurements .................................................................................................... 65
    4.3.1 CFL (Nuvue) measurements ............................................................................ 65
      4.3.1.1 Intensity Measurements with varying vibrational frequencies ................ 80
      4.3.1.2 Summary and discussion on CFL measurements ...................................... 81
    4.3.2 CFL (Ecosmart) Measurements ......................................................................... 81
      4.3.2.1 Intensity Measurements with varying vibrational frequencies ............... 100
      4.3.2.2 Long term no vibration test ....................................................................... 101
4.3.2.3 Summary and discussion on CFL (Ecosmart) measurements........ 102
4.5 Discussion.......................................................................................... 103

CHAPTER 5 CONCLUSIONS AND RECOMMENDATIONS......................... 104
  5.1 Conclusions ...................................................................................... 104
  5.2 Recommendations ............................................................................ 106

BIBLIOGRAPHY......................................................................................... 107

VITA............................................................................................................ 109
## LIST OF FIGURES

<table>
<thead>
<tr>
<th>Figure</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.1</td>
<td>Response of the Human Eye for Light</td>
</tr>
<tr>
<td>1.2</td>
<td>Photometric efficacies for different lamp sources</td>
</tr>
<tr>
<td>2.1</td>
<td>A diagram showing parts of incandescent bulb</td>
</tr>
<tr>
<td>2.2</td>
<td>A picture of fluorescent light and its parts</td>
</tr>
<tr>
<td>2.3</td>
<td>A photograph of led and its parts</td>
</tr>
<tr>
<td>2.4</td>
<td>A photograph of high power par30 26 degree led - warm white used for this work</td>
</tr>
<tr>
<td>3.1</td>
<td>A Schematic diagram illustrating the principle of electro-dynamic force generation</td>
</tr>
<tr>
<td>3.2</td>
<td>A photograph of model 113 shaker ELECTRO SEIS</td>
</tr>
<tr>
<td>3.3</td>
<td>Acceleration of various mass loads versus different frequencies</td>
</tr>
<tr>
<td>3.4</td>
<td>A photograph of the Function generator</td>
</tr>
<tr>
<td>3.5</td>
<td>Plot for frequency Vs amplitude</td>
</tr>
<tr>
<td>3.6</td>
<td>A figure and photograph showing the complete experimental setup</td>
</tr>
<tr>
<td>3.7</td>
<td>Experimental setup with proper dimensions</td>
</tr>
<tr>
<td>3.8</td>
<td>A schematic figure showing spectrometer and its parts</td>
</tr>
<tr>
<td>3.9</td>
<td>A photograph of USB 4000 ocean optics</td>
</tr>
<tr>
<td>3.10</td>
<td>A Schematic diagram showing the measurement set-up including the lamp, the axis (O) and the location of the spectrometer</td>
</tr>
<tr>
<td>3.11</td>
<td>A Drawing showing how to calculate cosθ</td>
</tr>
<tr>
<td>3.12</td>
<td>Response of human eye to light</td>
</tr>
<tr>
<td>4.1</td>
<td>A photograph of High Power PAR30 26 Degree LED - Warm White</td>
</tr>
<tr>
<td>4.2</td>
<td>Intensity versus angle at a distance of 30.74 inches from the source for various wavelengths (a) before vibrations (b) after vibrations at 5Hz for 24 hours</td>
</tr>
<tr>
<td>4.3</td>
<td>Intensity versus angle at a distance of 34.74 inches from the source for various wavelengths (a) before vibrations (b) after vibrations at 5Hz for 24 hours</td>
</tr>
<tr>
<td>4.4</td>
<td>Intensity versus angle at a distance of 39.74 inches from the source for various wavelengths (a) before vibrations (b) after vibrations at 5Hz for 24 hours</td>
</tr>
<tr>
<td>4.5</td>
<td>Intensity versus angle at a distance of 30.74 inches from the source for various wavelengths (a) before vibrations (b) after vibrations at 10Hz for 24 hours</td>
</tr>
<tr>
<td>4.6</td>
<td>Intensity versus angle at a distance of 34.74 inches from the source for various wavelengths (a) before vibrations (b) after vibrations at 10Hz for 24 hours</td>
</tr>
<tr>
<td>4.7</td>
<td>Intensity versus angle at a distance of 39.74 inches from the source for various wavelengths (a) before vibrations (b) after vibrations at 10Hz for 24 hours</td>
</tr>
<tr>
<td>4.8</td>
<td>Intensity versus angle at a distance of 30.74 inches from the source for various wavelengths (a) before vibrations (b) after vibrations at 15Hz for 24 hours</td>
</tr>
</tbody>
</table>
| 4.9    | Intensity versus angle at a distance of 34.74 inches from the source for
various wavelengths (a) before vibrations (b) after vibrations at 15Hz for 24 hours.

Figure 4.10 Intensity versus angle at a distance of 39.74 inches from the source for various wavelengths (a) before vibrations (b) after vibrations at 15Hz for 24 hours.

Figure 4.11 A plot showing frequency vs. intensity at 546.78nm

Figure 4.12 A photograph of Compact Fluorescent bulb R30 bulb - Warm White

Figure 4.13 Intensity versus angle at a distance of 30.74 inches from the source for various wavelengths (a) before vibrations (b) after vibrations at 5Hz for 24 hours.

Figure 4.14 Intensity versus angle at a distance of 34.74 inches from the source for various wavelengths (a) before vibrations (b) after vibrations at 5Hz for 24 hours.

Figure 4.15 Intensity versus angle at a distance of 39.74 inches from the source for various wavelengths (a) before vibrations (b) after vibrations at 5Hz for 24 hours.

Figure 4.16 Intensity versus angle at a distance of 30.74 inches from the source for various wavelengths (a) before vibrations (b) after vibrations at 10Hz for 24 hours.

Figure 4.17 Intensity versus angle at a distance of 34.74 inches from the source for various wavelengths (a) before vibrations (b) after vibrations at 10Hz for 24 hours.

Figure 4.18 Intensity versus angle at a distance of 39.74 inches from the source for various wavelengths (a) before vibrations (b) after vibrations at 10Hz for 24 hours.

Figure 4.19 Intensity versus angle at a distance of 30.74 inches from the source for various wavelengths (a) before vibrations (b) after vibrations at 15Hz for 24 hours.

Figure 4.20 Intensity versus angle at a distance of 34.74 inches from the source for various wavelengths (a) before vibrations (b) after vibrations at 15Hz for 24 hours.

Figure 4.21 Intensity versus angle at a distance of 39.74 inches from the source for various wavelengths (a) before vibrations (b) after vibrations at 15Hz for 24 hours.

Figure 4.22 A plot frequency versus intensity at 546.78nm

Figure 4.23 A photograph of Compact Fluorescent bulb Ecosmart - Warm White

Figure 4.24 Intensity versus angle at a distance of 30.74 inches from the source for various wavelengths (a) before vibrations (b) after vibrations at 5Hz for 24 hours (c) two days after vibrations.

Figure 4.25 Intensity versus angle at a distance of 34.74 inches from the source for various wavelengths (a) before vibrations (b) after vibrations at 5Hz for 24 hours (c) two days after vibrations.

Figure 4.26 Intensity versus angle at a distance of 39.74 inches from the source for various wavelengths (a) before vibrations (b) after vibrations at 5Hz for 24 hours (c) two days after vibrations.

Figure 4.27 Intensity versus angle at a distance of 30.74 inches from the source for
various wavelengths (a) before vibrations (b) after vibrations at 10Hz for 24 hours (c) two days after vibrations. .......................................................... 90

Figure 4.28  Intensity versus angle at a distance of 34.74 inches from the source for various wavelengths (a) before vibrations (b) after vibrations at 10Hz for 24 hours (c) two days after vibrations. .......................................................... 92

Figure 4.29  Intensity versus angle at a distance of 39.74 inches from the source for various wavelengths (a) before vibrations (b) after vibrations at 10Hz for 24 hours (c) two days after vibrations. .......................................................... 94

Figure 4.30  Intensity versus angle at a distance of 30.74 inches from the source for various wavelengths (a) before vibrations (b) after vibrations at 15Hz for 24 hours (c) two days after vibrations. .......................................................... 96

Figure 4.31  Intensity versus angle at a distance of 34.74 inches from the source for various wavelengths (a) before vibrations (b) after vibrations at 15Hz for 24 hours (c) two days after vibrations. .......................................................... 98

Figure 4.32  Intensity versus angle at a distance of 39.74 inches from the source for various wavelengths (a) before vibrations (b) after vibrations at 15Hz for 24 hours (c) two days after vibrations. .......................................................... 100

Figure 4.33  A plot showing frequency versus intensity at 546.78nm ......................... 101

Figure 4.34  A plot showing frequency versus intensity at 546.78nm ......................... 102
LIST OF TABLES

Table 1.1  Photometric Efficacies for different lamp sources ........................................ 5
Table 2.1  A comparison of A 60 W Incandescent and 13 W CFL ................................. 15
Table 2.2  Luminous efficacy and efficiency for several types of general service, 1000 hour lifespan incandescent bulb, and several idealized light sources [18] . 15
Table 2.3  Comparison of efficacy by power (120 Volt lamps) [18] ............................... 17
Table 2.4  Comparison of different lighting systems with various factors [28] .......... 30
Table 2.5  Energy Efficiency and Energy costs of Light emitting diodes, Incandescent and fluorescent lighting ......................................................... 31
Table 2.6  Light output for Different lighting systems (LED, Incandescent and CFLs) ................................................................................................................. 32
Table 3.1  Comparison of costs savings on the bulbs used in this work and normal incandescent bulb .............................................................. 40
Table 5.1  Summary of all the lamps at various angles and distances in different vibrational conditions................................................................. 104
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CHAPTER 1

INTRODUCTION

The modern world is an electrified world with electricity facilitating many of human activities, from providing light and allowing the operation of electrical large electrical equipment and small electronic devices. The light bulb, in particular, has profoundly changed human existence by illuminating the night and making it hospitable for a wide range of human activities.

Humphrey Davy, an English chemist, created first known artificial lighting using electricity in 1809. He used a high-powered battery to induce an electric current between two strips of charcoal. The current flow through the high impedance material induced light creating the first arc lamp [1]. Since then, at least three different types of lighting based on electricity- incandescent bulbs, fluorescent bulbs and light emitting diode bulbs, have been invented and developed in to commercial applications. Incandescent bulbs work based on the principle that when an electric current passes through a highly resistive medium, the filament heats up due to Joule ($I^2R$) losses and the filament gives out visible light. Since most filaments will interact with the oxygen in the atmosphere and oxidize, the filament has to be in a vacuum or inert atmosphere. Incandescent bulb went through an evolution starting with expensive platinum filament in vacuum to carbon and bamboo filament to finally inexpensive tungsten filament in an inert atmosphere.

The first three quarters of the 20th Century was dominated by the incandescent bulb based on tungsten filament which became commercial in 1910 [1]. Even though the incandescent bulb is still widely used throughout the world, especially, in the developing and under-development countries, a technology is inferior in energy efficiency and the
quality of optical output. In other words, optical output for a unit of electrical input is very low due to wastage of energy in heat. In addition, the spectrum of visible light produced does not match that of the natural sunlight.

![Standard eye sensitivity](image)

**Figure 1.1 Response of the Human Eye for Light**

The human eye is sensible to light wave which wavelength is roughly between 400 nm and 700 nm. When illumination is enough (in daylight), the maximum sensitivity is in the green region at 555 nm. This is photopic vision. The eye response is visible in the Fig 1.1 [2]

During the later part of the 20th Century, fluorescent lighting became prominent. The fluorescent light is a gas discharge tube that uses electricity to excite mercury vapor. The excited mercury vapor produce short wave ultraviolet lights that then causes a phosphor to fluorescence, producing visible light. The history of the fluorescent lamp begins with early research into electrical phenomena. By the beginning of the 18th century,
experimenters had observed a radiant glow emanating from partially evacuated glass vessels through which an electrical current passed. Little more done with this phenomenon until 1856 when a German glassblower named Heinrich Geissler (1815–1879) created a mercury vacuum pump that evacuated a glass tube to an extent not previously possible. When an electrical current passed through a Geissler tube, a strong green glow on the walls of the tube at the cathode end is observed [3]. One of the first scientists to experiment with a Geissler tube was Julius Plücker (1801–1868) who systematically described in 1858 the luminescent effects that occurred in a Geissler tube. Inquiries that began with the Geissler tube continued as even better vacuums were produced.

Research conducted by Crookes and others ultimately led to the discovery of the electron in 1897 by J. J. Thomson. A few years earlier another scientist, George G. Stokes (1819–1903), had noted that ultraviolet light caused fluorspar to fluoresce, a property that would become critically important for the development of fluorescent lights many decades later [4]. The development of the neon light also was significant for the last key element of the fluorescent lamp, its fluorescent coating. A team led by George E. Inman built a prototype fluorescent lamp in 1934 at General Electric. A great deal of experimentation had to be done on lamp sizes and shapes, cathode construction, gas pressures of both argon and mercury vapor, colors of fluorescent powders, methods of attaching them to the inside of the tube, and other details of the lamp and put them into public [4]. The team designed the first practical and viable fluorescent lamp (U>S> Patent No. 2,259,040) that was first sold in 1938 [5]. GE and Westinghouse publicized the new lights through exhibitions at the New York World’s Fair and the Golden Gate
International Exposition in San Francisco. Fluorescent lighting systems spread rapidly during World War II. By 1951, more light in the United States by fluorescent lamps than by incandescent lamps [5].

The next step was the improvement in lamp life when zirconia was a ‘glue’ to hold the emissions mix to the filaments. This increased the life from 2500 hours to 7500 hours [6]. Improving the process was the next development, by using mercury that is more pure and having better control of the phosphor size. The life of the lamp improved, from 7500 hours to 10,000 hours. In 1949, Soft White Bulb was manufactured which is the improved light dispersion and virtually glare-free. In 1959, Halogen Lamp Crisp, pure white light in a small was into market [8]. In the 1960’s electromagnetic ballasts were used as they were cheap and simple. They lasted a long time but had some issues such as causing buzzing or flickering of the lamps. Since then these improved, as it is imperative for the electronic ballast to work and be as efficient as the lamp itself [6]. In 1961 General Electric ever manufactured Lucalox® High-Pressure Sodium Lamps Highest efficacy general lighting source. Edward E. Hammer, an engineer with General Electric, in response to the 1973 oil crisis, invented the modern CFL. CFLs have steadily increased in sales volume [7]. The primary difference is in size; compact fluorescent bulbs are made in special shapes (which require special technologies) to fit in standard household light sockets, like table lamps and ceiling fixtures. In addition, most compact fluorescent lamps have “integral" ballast that is built into the light bulb, whereas most fluorescent tubes require separate ballast independent of the bulb. Both types offer energy-efficient light. Light Emitting Diode (LED) invented by GE in 1962 where electricity transforms into light inside a solid crystal of semiconductor material. In 1974 Watt-Miser®
Fluorescent Lamp First reduced-wattage fluorescent was into market [8].

<table>
<thead>
<tr>
<th>Source</th>
<th>lm/W</th>
</tr>
</thead>
<tbody>
<tr>
<td>Paraffin candle</td>
<td>0.1</td>
</tr>
<tr>
<td>Acetylene lamp</td>
<td>0.7</td>
</tr>
<tr>
<td>Edison's first lamp</td>
<td>1.6</td>
</tr>
<tr>
<td>Cellulose filament incandescent</td>
<td>2.6</td>
</tr>
<tr>
<td>Tungsten filament incandescent</td>
<td>10</td>
</tr>
<tr>
<td>(early high vacuum)</td>
<td></td>
</tr>
<tr>
<td>Tungsten filament incandescent</td>
<td>20</td>
</tr>
<tr>
<td>(early gas filled)</td>
<td></td>
</tr>
<tr>
<td>Tungsten filament incandescent</td>
<td>15</td>
</tr>
<tr>
<td>(modern $10^2$ W)</td>
<td></td>
</tr>
<tr>
<td>Tungsten filament incandescent</td>
<td>33</td>
</tr>
<tr>
<td>(modern $10^4$ W)</td>
<td></td>
</tr>
<tr>
<td>Early sodium lamp</td>
<td>20</td>
</tr>
<tr>
<td>Modern sodium lamp</td>
<td>150</td>
</tr>
<tr>
<td>Early mercury lamp</td>
<td>40</td>
</tr>
<tr>
<td>Early fluorescent lamp</td>
<td>55</td>
</tr>
<tr>
<td>Modern fluorescent lamp</td>
<td>70</td>
</tr>
<tr>
<td>(general purpose)</td>
<td></td>
</tr>
<tr>
<td>Gallium arsenide diode</td>
<td>180</td>
</tr>
<tr>
<td>&quot;Ideal&quot; source</td>
<td>685</td>
</tr>
</tbody>
</table>

Figure 1.2 Photometric Efficacies for different lamp sources

The LED is a semiconductor device made by juxtaposing an n-type (majority electrons) and p-type semiconductor (majority holes). Passing current through the device makes electrons and holes to recombine in device resulting in light output corresponding to the band gap energy of the semiconductor. The color of the light output directly relates to the band gap of the material [9].

Electroluminescence came into existence in 1907 by the British experimenter H. J. Round of Marconi Labs, using a crystal of silicon carbide and a cat's-whisker detector. Rubin Braunstein of the Radio Corporation of America reported on infrared emission from gallium arsenide (GaAs) and other semiconductor alloys in 1955 [9]. In 1961,
experimenters found that GaAs emitted infrared radiation when electric current applied and they received the patent for the infrared LED. The first practical visible-spectrum (red) LED developed in 1962 by Nick Holonyak Jr., while working at General Electric Company [12]. In 1976, T.P. Pearsall created the first high-brightness; high efficiency LEDs for optical fiber telecommunications by inventing new semiconductor materials specifically adapted to optical fiber transmission wavelengths. The first commercial LEDs were commonly used as replacements for incandescent indicators, and in seven-segment displays, first in expensive equipment such as laboratory and electronics test equipment, then later in such appliances as TVs, radios, telephones, calculators, and even watches.

The invention and development of the high power white light LED led to use for illumination. LEDs have been around since the 60s, but relegated to showing the time in an alarm clock or the battery level of a video camera. They were not sources of illumination because of lack of LEDs that can produce white light. Nichia Chemical of Japan changed that in 1993 when it started producing blue LEDs, which combined with red and green which produced white light [10]. This advancement has opened up a completely new field for the technology.

The first high-brightness blue LED was demonstrated by Shuji Nakamura of Nichia Corporation and was based on InGaN borrowing on critical developments in GaN nucleation on sapphire substrates and the demonstration of p-type doping of GaN that were developed by Isamu Akasaki and H. The advances attributed to the parallel development of other semiconductor technologies and advances in optics and material science. In February 2008, Bilkent University in Turkey reported 300 lumens of visible
light per watt luminous efficacy (not per electrical watt) and warm light by using nano-crystals [9]. In January 2009, researchers from Cambridge University reported a process for growing gallium nitride (GaN) LED luminaires on silicon. Production costs reduced by 90% using six-inch silicon wafers instead of two-inch sapphire wafers. Colin Humphreys [9] led the team. Therefore, the LED luminaires are most energy efficient though DOE high compare the initial cost to other lamps many developments are in process for obtaining more energy efficiency.

Let us compare all the three major types of lighting where we discriminate these 3 types in color temperature, color rendering index (CRI), and light output in Lumen. Incandescent lights are the least expensive, but the shortest lasing at ~ 1500-2000 hours [11]. This type of lighting inefficiently creates an over abundance of secondary heat. Fluorescent lighting that is moderately priced lasts 5000-8000 hours (4 times longer than incandescent) [11]. This type of lighting is available in warm and cold varieties and is ~4 times more efficient than incandescent. Fluorescent lights do not operate well at low temperatures and must come up to operating temperatures before maximum light output. Mercury is a concern when disposing of these bulbs, and they tend to heat up when lit for a time. Light Emitting Diode lighting is rather expensive but last upwards of 50,000 to even 100,000 hours [11]. LED luminaires are moisture, vibration and shock resistant, and instantly obtain maximum output. Most LED lights produce a low lumen for their respective size. LED light bulbs are true watt misers being ~ 20times more efficient than incandescent, and they remain very cool to the touch. Like fluorescent lights, different color temperatures are available for warm or cool lighting. LEDs also come in many color varieties.
The Department of Energy has estimated that LED lighting could cut national energy consumption for lighting by 29% by 2025. The total savings on U.S. household electric bills until then would be $125 billion. LEDs have other advantages that are propelling them into niche uses, despite their upfront cost. White LEDs commercially available today will last up to 50,000 hours, about 50 times as long as a 60-W incandescent bulb [12].

LEDs produce monochromatic radiation and the color tone defined by the dominant wavelength. There are LEDS in the colors of Red, Orange, Blue, Green, and Yellow. White light is a mixture of wavelengths. A blue LED coated with a white phosphor, when blue light hits the inner surface of the phosphor, it emits white light. This technology is now in commercial applications, but there are still some worries about the life cycle of the technology. It has been noted that the phosphor can degrade, reducing the light output, over a period of years. The second method of producing white light is to use additive mixing of the three primary colors red, green and blue. This scheme is finding some applications, but by the nature of additive mixing, the white tends not to be very even in its spectrum.

In early 1994, Artistic License prototyped what is believed to be the first full color mixing design using red, green and blue LEDs [13]. The design used pulse width modulation of each color channel, with a Zilog Z8 microprocessor receiving the color request via the relatively new DMX512 protocol. The principal worked, but the LED brightness and cost was such that the design could not yet become a product.

The luminous flux value of currently available LEDs lies between one lumen (lm) in low performance LEDs (about 50 to 100 MW power input) and up to 120 lm in high
performance LEDs (up to 5 W) [14]. Stronger evidence for end users is the information on the luminous flux packets, which realized with LED modules. Many advantages of LED is making it leading in today’s world. The advantages of LEDS are low power consumption compared to conventional lighting, No ultra-violet output. The UV component of conventional lighting can cause damage to fabric. Very little heat is produced as the light output, reducing the cost of building air conditioning and allowing lighting to fit into positions too small for conventional lights. Lamp life is very long, most LED luminary manufacturers estimate 100,000 hours. Ecologically friendly, lightweight manufacture and colored light can be produced [14].

Lifespan depends on temperature mainly and many other factors that are too made into standards by the DOE. Some standards established from many reports. The lifespan of an LED depends on its operational, environmental temperature and environmental conditions. At room temperature, LED luminaires – and thus LED modules – have a very long lifespan of up to 50,000 working hours. In contrast to filament lamps, where a break in the helix means the end of its life, total failure of an LED luminary is extremely rare. Its light intensity also declines much more slowly, this property known as degradation. The period of degradation of the original luminous flux by up to 50 % defines the lifespan of LED luminaires. The light intensity distribution curves of LED luminaires determined by the construction of the housing used. The angle of radiation can vary between 15 and 160 degrees.

In June 2008, the Illuminating Engineering Society of North America (IESNA) published a documentary standard LM-79 entitled "Electrical and Photometric Measurements of Solid-State Lighting Products." This describes the methods for testing
SSL products for their photometric characteristics such as total luminous flux (lumens), luminous efficacy (lm/W), luminous intensity (candels) in one or more directions, chromaticity coordinates, correlated color temperature (CCT) and color rendering index (CRI) [15]. The most substantial part of LM-79 describes test methods for total luminous flux measurement, which carries out with an integrating sphere or a goniophotometer. Crucially, LM-79 specifies absolute, rather than relative, photometry. For other light sources and luminaires, there are separate standards for the measurement of lamps or luminaires. However, because in many current SSL products the LED light source(s) in the luminaires are not easily separable as replaceable lamps; the existing standards cannot be applied directly to SSL products. The LM-79 document says, "Since SSL technologies are still at their early stages, requirements for measurement conditions and appropriate measurement techniques may be subject to change at any time."[15]

The DOE (Department of energy) conducted L-Prize competition, which launched in 2007 with a view to energy independence and security of the United States by developing and introducing energy efficient LED lighting products to the commercial and residential markets. The competition requirements include lm/W, power consumption, total light output, lifetime and CRI more than 90 [16]. Obviously, lighting products in commercial and residential settings will be subjected to various environmental and user specific conditions. For example, in a commercial setting the lights may be on for 12 hours, mostly during daytime, whereas, in a residential setting, the lights may be on 6 hours a day, mostly during nighttime [16]. The ambient in these settings may fluctuate in temperature and humidity. Depending on whether it is a hot summer day or cold snowy winter day, the outdoor conditions may vary substantially in temperature and humidity.
fluctuations. In addition, depending on the energy demand (may change from residential to commercial), there will also be power fluctuations. On additional environmental condition to consider is vibration resulting from machinery and earthquakes. Many factors affect the efficiency of LED luminaires such as humidity, temperature, dimming, vibrations, etc.

One of the main environmental parameters in industrial settings and oilrigs is vibration. For successful adoption of LED luminaires in such settings requires a thorough study of effect of vibration on LED luminaires. Hence, this thesis work focuses on the effect on the performance (optical output) of vibration on LED luminaires. As part of this work, an experimental setup for creating controlled vibrations of set amplitude and or frequency is developed along with a goniometer to measure the light intensity at various angles and distances from the luminaires. In chapter 2, a literature survey of several related topics is presented. In Chapter 3 experimental setup along with the experimental procedure are described. Results and discussions are presented in Chapter 4. Conclusions and recommendations for future work are in the chapter 5.
CHAPTER 2

LITERATURE SURVEY

In this chapter, a thorough literature survey of developments covering incandescent, fluorescent and light emitting diode-based lighting are provided. Wherever possible and necessary, the different technologies are contrasted and the new developments related to a specific need.

2.1 Incandescent Lighting

Humphrey Davy, an English chemist, in 1809 used a high-powered battery to induce an electric current between two strips of charcoal. The current flow through the high impedance material induced light creating the first arc lamp [17]. In 1820, Warren De La Rue made the first known attempt to produce an incandescent light bulb [17]. He enclosed a platinum coil in an evacuated tube and passed an electric current through it. The design based on the ideas that (i) the high melting point of platinum would allow it to operate at high temperature and (ii) evacuated chamber atmosphere would contain less gas particles to react with the platinum. Later in 1840, William Robert Grove, succeeded in lighting an auditorium using a similar approach [17]. The lamps constructed of platinum coils encased in an inverted glass sealed by water. Unfortunately, platinum coil lamps were too expensive and impractical for commercial use. Frederick de Moleyns in 1841 received the first patent for an incandescent lamp [18]. The design specifications involved mounting a powered charcoal filament between two platinum wires in an evacuated glass bulb. As the filament reacted at high temperature with air, the air present in the lamp was evacuated to extend filament life. In 1845, W.E.Staite, an American, patented a second incandescent electric lamp [19]. Thomas Wright obtained the first
In mid 1800’s, Edward G. Sheppard, made an incandescent lamp using a charcoal filament [17]. Joseph Wilson swan, started work on carbon filament using paper. Carbon filaments provided a low cost and practical filament material based on technology in 1850 [20]. In 1854, Heinrich Gobel a German used carbonized bamboo filament secured in a glass container [19]. C. de.Chagny, a French engineer, patented an incandescent lamp with a platinum filament for use by workers in 1856 [17]. In 1875, Herman Sprengel invented the mercury vacuum pump making it possible to develop a practical electric light bulb [17] facilitating excellent evacuation of inside of the bulb possible. Henry Woodward and Matthew Evans patented a light bulb in 1874 [21].

In 1878, Sir Joseph Wilson Swan, an English physicist, was the first person to invent a practical and longer-lasting electric light bulb, which burnt for 13.5 hours [17]. In 1879, Thomas Alva Edison invented a carbon filament that burned for forty hours [17]. Edison placed his filament in oxygen less bulb. Edison evolved his designs for the light bulb based on the 1875 patent [21] that he had purchased from the inventors, Henry Woodward and Matthew Evans. In 1880, Edison continued to improve his light bulb until it could last for over 1200 hours using a bamboo-derived filament [17]. In 1903, Willis Whit new invented a filament that would not make the inside of a light bulb turn dark. It was a metal-coated carbon filament, a predecessor to the tungsten filament [18].

The General Electric Company was the first to patent a method of making tungsten filaments for use in incandescent light bulbs [18]. The filaments were costly. In 1910, William David Coolidge invented an improved method of making tungsten filaments [17]. The tungsten filament outlasted all other types of filaments and in addition was
inexpensive. The first frosted light bulb was produced in 1925 by GE lighting.

The new high efficiency incandescent (HEI™) lamp, which incorporates innovative new materials being developed in partnership by GE’s Lighting division, headquartered in Cleveland, Ohio, and GE’s Global Research Center, headquartered in Niskayuna, NY, would replace traditional 40 to 100 Watt household incandescent light bulbs, the most popular lamp type used by consumers today [22]. There could be expansion of new technology to all other incandescent types as well. The target for these bulbs at initial Ultimately the high efficiency lamp (HEI) technology is expected to be about four times as efficient as current incandescent bulbs and comparable to CFL bulbs. Adoption of new technology could lead to greenhouse gas emission reductions of up to 40 million tons of CO2 in the U.S. and up to 50 million tons in the EU if the entire installed base of traditional incandescent bulbs was replaced with HEI lamps, production is to be nearly twice as efficient, at 30 lumens-per-Watt, as current incandescent bulbs [22]. In addition to offering significant energy savings comparable to CFLs, the 21st century version of Edison’s bulb provides all the desirable benefits including light quality and instant-on convenience as incandescent lamps currently provide at a price that will be less than CFLs [22].
Table 2.1 A comparison of A 60 W Incandescent and 13 W CFL

<table>
<thead>
<tr>
<th>Categories (units)</th>
<th>Incandescent</th>
<th>CFL</th>
</tr>
</thead>
<tbody>
<tr>
<td>Watts consumed (W)</td>
<td>60</td>
<td>13</td>
</tr>
<tr>
<td>Rated Lamp Life (hours)</td>
<td>1000</td>
<td>8,000</td>
</tr>
<tr>
<td>Electricity cost per kWh ($/kWh)</td>
<td>0.1</td>
<td>0.1</td>
</tr>
<tr>
<td>Cost per bulb ($)</td>
<td>0.25</td>
<td>3</td>
</tr>
</tbody>
</table>

Table 2.2 Luminous efficacy and efficiency for several types of general service, 1000-hour lifespan incandescent bulb, and several idealized light sources [18].

<table>
<thead>
<tr>
<th>Type</th>
<th>Overall luminous efficiency</th>
<th>Overall luminous efficacy (lm/W)</th>
</tr>
</thead>
<tbody>
<tr>
<td>40 W tungsten incandescent</td>
<td>1.90%</td>
<td>12.6</td>
</tr>
<tr>
<td>60 W tungsten incandescent</td>
<td>2.10%</td>
<td>14.5</td>
</tr>
<tr>
<td>100 W tungsten incandescent</td>
<td>2.60%</td>
<td>17.5</td>
</tr>
<tr>
<td>Glass halogen</td>
<td>2.30%</td>
<td>16</td>
</tr>
<tr>
<td>Quartz halogen</td>
<td>3.50%</td>
<td>24</td>
</tr>
<tr>
<td>High-temperature incandescent</td>
<td>5.10%</td>
<td>35</td>
</tr>
<tr>
<td>Ideal black-body radiator at 4000 K</td>
<td>7.00%</td>
<td>47.5</td>
</tr>
<tr>
<td>Ideal black-body radiator at 7000 K</td>
<td>14%</td>
<td>95</td>
</tr>
<tr>
<td>Ideal monochromatic 555 nm (green) source</td>
<td>100%</td>
<td>683</td>
</tr>
</tbody>
</table>
There are several drawbacks to incandescent light bulbs. Incandescent light bulbs use significantly more electricity than other light emitting bulbs such as fluorescent bulbs. Depending on the cost of your electricity, average savings for using fluorescent lighting for comparable incandescent bulbs may be $60-$75 per year assuming 4 hours of usage a day. The incandescent bulb works by heating the filament [23]. Ninety percent of the energy used converted to heat [23]. In addition, when the incandescent bulb burns out you must wait for it to cool before you change it, or protect your fingers from burns. The quality of incandescent light is poor. Poultry farms avoid raising fowl under incandescent lights because it can cause self-destructive stress in the birds. Incandescent light bulbs have a relatively short life span. Many other light systems such as the fluorescent will last up to 13 times as long. The main hazard of an incandescent bulb is breaking off in the light socket. If you have, light fixtures mounted high up on the ceiling and an incandescent light bulb breaks, replacing it hard [23].

Figure 2.1 A Diagram showing parts of Incandescent bulb
Table 2.3 Comparison of efficacy by power (120 Volt lamps) [18]

<table>
<thead>
<tr>
<th>Power (W)</th>
<th>Output (lm)</th>
<th>Efficacy (lm/W)</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>25</td>
<td>5</td>
</tr>
<tr>
<td>15</td>
<td>110</td>
<td>7.3</td>
</tr>
<tr>
<td>25</td>
<td>200</td>
<td>8.0</td>
</tr>
<tr>
<td>35</td>
<td>350</td>
<td>10.0</td>
</tr>
<tr>
<td>40</td>
<td>500</td>
<td>12.5</td>
</tr>
<tr>
<td>50</td>
<td>700</td>
<td>14.0</td>
</tr>
<tr>
<td>55</td>
<td>800</td>
<td>14.5</td>
</tr>
<tr>
<td>60</td>
<td>850</td>
<td>14.2</td>
</tr>
<tr>
<td>65</td>
<td>1,000</td>
<td>15.4</td>
</tr>
<tr>
<td>70</td>
<td>1,100</td>
<td>15.7</td>
</tr>
<tr>
<td>75</td>
<td>1,200</td>
<td>16.0</td>
</tr>
<tr>
<td>90</td>
<td>1,450</td>
<td>16.1</td>
</tr>
<tr>
<td>95</td>
<td>1,600</td>
<td>16.8</td>
</tr>
<tr>
<td>100</td>
<td>1,700</td>
<td>17.0</td>
</tr>
<tr>
<td>135</td>
<td>2,350</td>
<td>17.4</td>
</tr>
<tr>
<td>150</td>
<td>2,850</td>
<td>19.0</td>
</tr>
<tr>
<td>200</td>
<td>3,900</td>
<td>19.5</td>
</tr>
<tr>
<td>300</td>
<td>6,200</td>
<td>20.7</td>
</tr>
</tbody>
</table>

2.2 Fluorescent Lighting

The fluorescent light is a gas discharge tube that uses electricity to excite mercury vapor. The excited mercury vapor produce short wave ultraviolet lights that then causes a phosphor to fluorescence, producing visible light. The history of the fluorescent lamp begins with early research into electrical phenomena. By the beginning of the 18th century, experimenters had observed a radiant glow emanating from partially evacuated glass vessels through which an electrical current passed. Little more could be done with this phenomenon until 1856 when a German glassblower named Heinrich Geissler
(1815–1879) created a mercury vacuum pump that evacuated a glass tube to an extent not previously possible [3]. When an electrical current passed through a Geissler tube, a strong green glow on the walls of the tube at the cathode end is observed [3]. One of the first scientists to experiment with a Geissler tube was Julius Plücker (1801–1868) who systematically described in 1858 the luminescent effects that occurred in a Geissler tube [3]. Inquiries that began with the Geissler tube continued as even better vacuums were produced.

Research conducted by Crookes and others ultimately led to the discovery of the electron in 1897 by J. J. Thomson [4]. A few years earlier another scientist, George G. Stokes (1819–1903), had noted that ultraviolet light caused fluorspar to fluoresce, a property that would become critically important for the development of fluorescent lights many decades later [4]. The development of the neon light also was significant for the last key element of the fluorescent lamp, its fluorescent coating. A team led by George E. Inman built a prototype fluorescent lamp in 1934 at General Electric. A great deal of experimentation had to be done on lamp sizes and shapes, cathode construction, gas pressures of both argon and mercury vapor, colors of fluorescent powders, methods of attaching them to the inside of the tube, and other details of the lamp and put them into public [5]. The team designed the first practical and viable fluorescent lamp (U.S. Patent No. 2,259,040) that first sold in 1938 [5]. GE and Westinghouse publicized the new lights through exhibitions at the New York World’s Fair and the Golden Gate International Exposition in San Francisco. Fluorescent lighting systems spread rapidly during World War II. By 1951, more lights in the United States by fluorescent lamps than by incandescent lamps [5].
The next step was the improvement in lamp life when zirconia used as a ‘glue’ to hold the emissions mix to the filaments. This increased the life from 2500 hours to 7500 hours [6]. Improving the process was the next development, by using more mercury that is pure and having better control of the phosphor size. The life of the lamp improved, from 7500 hours to 10,000 hours [6]. In 1949, Soft White Bulb was manufactured which is the improved light dispersion and virtually glare-free [8]. In 1959, Halogen Lamp Crisp, pure white light in a small was into market. In the 1960’s electromagnetic ballasts were used, as they were cheap and simple [6]. They lasted a long time but had some issues such as causing buzzing or flickering of the lamps. Since then these improved, as it is imperative for the electronic ballast to work and be as efficient as the lamp itself [6]. In 1961, General Electric [8] ever manufactured Lucalox® High-Pressure Sodium Lamps Highest efficacy general lighting source. Edward E. Hammer, an engineer with General Electric, in response to the 1973 oil crisis, invented the modern CFL [7]. The development of very stable phosphors with a narrow band emission opened the
way to further miniaturization of fluorescent lamps. A discussion presented the present possibilities to reduce lamp dimensions to degree that makes them suitable for lighting. Reduction of length is essential according to the experimental data the balance considered between this desired reduction in length and accompanying effects as loss of efficacy and increase of ballast volume. This leads to an optimum discharge diameter, which is between 10 and 15mm, depending on the level of luminous flux. Lamps with this diameter are bent in order to arrive at an acceptable length. Then the compact fluorescents came into existence. The primary difference is in size; compact fluorescent bulbs are made in special shapes (which require special technologies) to fit in standard household light sockets, like table lamps and ceiling fixtures. In addition, most compact fluorescent lamps have “integral" ballast that is built into the light bulb, whereas most fluorescent tubes require separate ballast independent of the bulb. Both types offer energy-efficient light. Light Emitting Diode (LED) invented by GE in 1962 where electricity transforms into light inside a solid crystal of semiconductor material. In 1974 Watt-Miser® Fluorescent Lamp First reduced-wattage fluorescent was into market [8].

The average rated life of a CFL is between eight and 15 times that of incandescent [5]. CFLs typically have a rated lifespan of between 6,000 and 15,000 hours, whereas incandescent lamps manufactured to have a lifespan of 750 hours or 1,000 hours [5]. Some incandescent bulbs with long rated lifespan of 20,000 hours have reduced light output. The lifetime of any lamp depends on many factors including operating voltage, manufacturing defects, exposure to voltage spikes, mechanical shock, frequency of cycling on and off, lamp orientation and ambient operating temperature, among other factors. The life of a CFL is significantly shorter if it is only turned on for a few minutes.
at a time: In the case of a 5-minute on/off cycle the lifespan of a CFL can be up to 85% shorter, reducing its lifespan to "close to that of incandescent light bulbs" [5].

Mercury’s toxicity is major issue for CFLs. Many manufacturers have been able to reduce the mercury content to less than 5 mg per bulb and are working on further reductions [24]. CFLs contain a small amount of mercury; they still contribute less mercury to the environment than incandescent bulbs. CFLs use only one-quarter to one-fifth the electricity that incandescent do—the less electricity is produced at coal-fired power plants, the less mercury spewed into the air [24]. CFLs can burn out prematurely if you frequently turn them on and off. As recommended by the experts CFLs used where they are left on for extended periods, and turn them off only when you will be out of a room for more than 15 minutes. It might be more cost effective for you to leave the lights on instead of causing your more expensive CFLs to burn out prematurely [24].

2.3 Light Emitting Diode Based Lighting

2.3.1 Light Emitting Diode Development

The LED is a semiconductor device made by juxtaposing an n-type (majority electrons) and p-type semiconductor (majority holes). Passing current through the device makes electrons and holes to recombine in device resulting in light output corresponding to the band gap energy of the semiconductor. The color of the light output directly relates to the band gap of the material [9].

LED lamps typically use less power (watts) per unit of light generated (lumens). A good LED lamp can generate twice as many lumens per watt as a CFL (50-100+ versus 40-80), also has less greenhouse gas emissions from power plants, lower electric bills. LED lamps last much longer than CFLs, as much as 10x longer (50,000 hours versus
5,000 hours), fewer spent lamps in the landfill, less frequent lamp purchasing/changing, especially important for hard-to-reach lamp locations. LED lamps generate less heat than CFLs, so they have decreased load on Air Conditioning systems, reduced danger of burns from touching lamps and reduced fire hazards [25].

Electroluminescence discovered in 1907 by the British experimenter H. J. Round of Marconi Labs, using a crystal of silicon carbide and a cat's-whisker detector [10]. Rubin Braunstein of the Radio Corporation of America reported on infrared emission from gallium arsenide (GaAs) and other semiconductor alloys in 1955 [10]. In 1961, experimenters found that GaAs emitted infrared radiation when electric current applied and they received the patent for the infrared LED. The first practical visible-spectrum (red) LED developed in 1962 by Nick Holonyak Jr., while working at General Electric Company [10].

The invention and development of the high power white light LED led to use for illumination. LEDs have been around since the 60s, but relegated to showing the time in an alarm clock or the battery level of a video camera. They not used as sources of illumination because of lack of LEDs that can produce white light. Nichia Chemical of Japan changed that in 1993 when it started producing blue LEDs, which combined with red and green produced white light. This advancement has opened up a completely new field for the technology. By 1997, Nichia had very high brightness blue and green LED’s and Hewlett Packard (Agilent) were producing very high brightness red LED’s. This was the year that the brightness – cost ratio crossed the critical line on the graph. It was now possible to produce products using the concept. It is expected that more companies will commence manufacturing LED solutions over the coming years. The initial costs per unit
reduction fuelled primarily by the use of LED’s in Traffic Lights and ‘Third' Brake Lights. As the volume continues to increase, prices will drop further [10]. This advancement has opened up a completely new field for the technology.

The first high-brightness blue LED was demonstrated by Shuji Nakamura of Nichia Corporation and was based on InGaN borrowing on critical developments in GaN nucleation on sapphire substrates and the demonstration of p-type doping of GaN, which were developed, by Isamu Akasaki and H [12]. The advances attributes to the parallel development of other semiconductor technologies and advances in optics and material science. In February 2008, Bilkent University in Turkey reported 300 lumens of visible light per watt luminous efficacy (not per electrical watt) and warm light by using Nano crystals [12]. In January 2009, researchers from Cambridge University reported a process for growing gallium nitride (GaN) LEDs on silicon. Production cost reduces by 90% using six-inch silicon wafers instead of two-inch sapphire wafers. Colin Humphreys [12] led the team. Therefore, the LEDs are most energy efficient though DOE high compare the initial cost to other lamps many developments are in process for obtaining more energy efficiency.

2.3.2 LED Luminaires for Lighting

In 1961, experimenters found that GaAs emitted infrared radiation when electric current applied and they received the patent for the infrared LED. The first practical visible-spectrum (red) LED developed in 1962 by Nick Holonyak Jr., while working at General Electric Company. In 1976, T.P. Pearsall created the first high-brightness; high efficiency LEDs for optical fiber telecommunications by inventing new semiconductor materials specifically adapted to optical fiber transmission wavelengths.
The first commercial LEDs were commonly used as replacements for incandescent indicators, and in seven-segment displays, first in expensive equipment such as laboratory and electronics test equipment, then later in such appliances as TVs, radios, telephones, calculators, and even watches [9].

LEDs have been around since long time, but relegated to showing the time in an alarm clock or the battery level of a video camera. They are not used as sources of illumination because of lack of LEDs that can produce white light. Nichia Chemical of Japan changed that in 1993 when it started producing blue LEDs, which combined with red and green produced white light. This advancement has opened up a completely new field for the technology [9]. By 1997, Nichia had very high brightness blue and green LED’s and Hewlett Packard (Agilent) were producing very high brightness red LED’s. This was the year that the brightness – cost ratio crossed the critical line on the graph. It was now possible to produce products using the concept.

There are two ways to produce white light from LEDs. In the first approach, a blue LED coated with a white phosphor produces white light [9]. This technology now in commercial applications, but there are still some worries about the life cycle of the technology. It has been noted that the phosphor can degrade, reducing the light output, over a period of years. Current life estimates are of the order of 6 years [12].

The second method of producing white light is to use additive mixing of the three primary colors red, green and blue. This scheme is finding some applications, but by the nature of additive mixing, the white tends not to be very even in its spectrum. Jerry Laidman at a company called Sound Chamber [12] implemented the concept of mixing the light output of LED’s in 1979. The product named ‘Saturn’ involved a spinning propeller.
Each of the three wings of the propeller consisted of circuit boards fitted with red, green and yellow LED’s. Each of the LED’s was controlled by pulse width modulation (PWM) allowing the intensity of each individual LED to be controlled. With the propeller spinning, the product could generate a huge number of colors.

![Diagram of LED and its parts]

In 1993 high brightness, blue LEDs demonstrated through the work of Shuji Nakamura at Nichia Corporation [9]. By the late 1990s, blue LEDs had become widely available. They have an active region consisting of one or more InGaN quantum wells sandwiched between thicker layers of GaN, called cladding layers. By varying the relative InN - GaN fraction in the InGaN quantum wells, the light emission varied from violet to amber. With nitrides containing aluminum, most often AlGaN and AlGaInN, even shorter wavelengths are achievable [9]. In early 1994, Artistic License prototyped what is believed to be the first full color mixing design using red, green and blue LED’s.
The design used pulse width modulation of each color channel, with a Zilog Z8 microprocessor receiving the color request via the relatively new DMX512 protocol [9]. The principal worked, but the LED brightness and cost was such that the design could not yet become a product.

The luminous flux value of currently available LED luminaires lies between one lumen (lm) in low performance LEDs (about 50 to 100 MW power input) and up to 120 lm in high performance LEDs (up to 5 W). Stronger evidence for end users is the information on the luminous flux packets, which realized with LED modules.

There are many advantages of LED luminaires, which is why it is the leading in today’s world. The advantages of LED luminaires are low power consumption compared to conventional lighting, No ultra-violet output. The UV component of conventional lighting can cause damage to fabric; Very little heat is produced in the light output, reducing the cost of building air conditioning and allowing lighting to fit into positions too small for conventional lights; Lamp life is very long; most LED manufacturers estimate 100,000 hours; Ecologically friendly; Light weight manufacture; Colored light can be produced.

Lifespan depends on temperature mainly and many other factors that are made into standards by the DOE [12]. Some standards established from various reports from different companies. The lifespan of an LED depends on its operational, environmental temperature and environmental conditions. At room temperature, LEDs – and thus LED modules – have a very long lifespan of up to 50,000 working hours [13]. In contrast to filament lamps, where a break in the helix means the end of its life, total failure of an LED is extremely rare. Its light intensity also declines much more slowly: this property is
degradation. The period of degradation of the original luminous flux by up to 50% defines the lifespan of LEDs. The light intensity distribution curves of LEDs determined by the construction of the housing used. The angle of radiation can vary between 15° and 160° [13].

At the beginning of 2008, the American National Standard Lighting Group (ANSLG) published ANSI_NEMA_ANSLG C78.377-2008 entitled "Specifications for the Chromaticity of Solid State Lighting Products" [15]. This standard specifies the range of chromaticity recommended for general indoor lighting with SSL products, and ensures that the white light chromaticity of the products communicated to consumers. In addition, the standard covers fixtures incorporating light sources as well as integrated LED lamps, and excludes fixtures sold without a light source.

In June 2008, the Illuminating Engineering Society of North America (IESNA) published a documentary standard LM-79 entitled "Electrical and Photometric Measurements of Solid-State Lighting Products" [15]. This describes the methods for testing SSL products for their photometric characteristics such as total luminous flux (lumens), luminous efficacy (lm/W), luminous intensity (candelas) in one or more directions, chromaticity coordinates, correlated color temperature (CCT) and color rendering index (CRI). The most substantial part of LM-79 describes test methods for total luminous flux measurement, which carried out with an integrating sphere or a goniophotometer. Crucially, LM-79 specifies absolute, rather than relative, photometry. For other light sources and luminaires, there are separate standards for the measurement of lamps or luminaires. However, because in many current SSL products the LED light source(s) in the luminaires are not easily separable as replaceable lamps; the existing
standards cannot directly apply to SSL products. The LM-79 document says, "Since SSL technologies are still at their early stages, requirements for measurement conditions and appropriate measurement techniques may be subject to change at any time." [15]

The Department of Energy has estimated that LED lighting could cut national energy consumption for lighting by 29% by 2025 [26]. The total savings on U.S. household electric bills until then would be $125 billion. LEDs have other advantages that are propelling them into niche uses, despite their upfront cost. Current white LEDs will last up to 50,000 hours, about 50 times as long as a 60-watt bulb. That is almost six years if they are on constantly.

The DOE (Department of Energy) conducted L-Prize competition, which was launched in 2007 [27] with a view to energy independence and security of the United States by developing and introducing energy efficient LED lighting products to the commercial and residential markets. The competition requirements include lm/W, power consumption, total light output, lifetime and CRI more than 90. Obviously, lighting products in commercial and residential settings will be subjected to various environmental and user specific conditions. For example, in a commercial setting the lights may be on for 12 hours, mostly during daytime, whereas, in a residential setting, the lights may be on 6 hours a day, mostly during nighttime [27]. The ambient in these settings may fluctuate in temperature and humidity. Depending on whether it is a hot summer day or cold snowy winter day, the outdoor conditions may vary substantially in temperature and humidity fluctuations. In addition, depending on the energy demand (may change from residential to commercial); there will also be power fluctuations. On additional environmental condition to consider is vibration resulting from machinery and
earthquakes. Many factors affect the efficiency of LEDs such as humidity, temperature, dimming, vibrations, etc.

Figure 2.4 A photograph of High Power PAR30 26 Degree LED - Warm White used for this work.

2.4 Summary of Various lighting systems

Various factors have been discussed which effect the three different kinds of lighting systems which play an important role in the environment. All the factors are formatted into a table and compared below as shown below.
Table 2.4 Comparison of different lighting systems with various factors [28]

<table>
<thead>
<tr>
<th>Factors</th>
<th>Light Emitting Diodes Luminaires (LEDs)</th>
<th>Incandescent Light Bulbs</th>
<th>Compact Fluorescents (CFLs)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sensitivity to low temperatures</td>
<td>None</td>
<td>Some</td>
<td>Yes - may not work under negative 10º F or over 120º F</td>
</tr>
<tr>
<td>Sensitive to humidity</td>
<td>Sensitive to humidity</td>
<td>Some</td>
<td>Yes</td>
</tr>
<tr>
<td>Turns on instantly</td>
<td>Yes</td>
<td>Yes</td>
<td>No - takes time to warm up</td>
</tr>
<tr>
<td>Durability</td>
<td>Very Durable - can handle jarring and bumping</td>
<td>Not Very Durable - glass or filament can break easily</td>
<td>Not Very Durable - glass can break easily</td>
</tr>
<tr>
<td>Failure Modes</td>
<td>Not typical</td>
<td>Some</td>
<td>Yes - may catch on fire, smoke, or omit an odor</td>
</tr>
<tr>
<td>Environmental Impact</td>
<td>Light Emitting Diodes</td>
<td>Incandescent Light Bulbs</td>
<td>Compact Fluorescents</td>
</tr>
<tr>
<td>Contains the TOXIC Mercury</td>
<td>No</td>
<td>No</td>
<td>Yes - Mercury is very toxic to your health and the environment</td>
</tr>
<tr>
<td>RoHS Compliant</td>
<td>Yes</td>
<td>Yes</td>
<td>No - contains 1mg-5mg of Mercury and is a major risk to the environment</td>
</tr>
<tr>
<td>Carbon Dioxide Emissions (30 bulbs per year)</td>
<td>451 pounds/year</td>
<td>4500 pounds/year</td>
<td>1051 pounds/year</td>
</tr>
</tbody>
</table>

2.5 Comparing Incandescent, CFL, LED luminaires

Let us compare all the three major types of lighting where we discriminate these 3
types in color temperature, color rendering index (CRI), and light output in Lumen. Incandescent lights are the least expensive, but the shortest lasing at ~ 1500-2000 hours. This type of lighting inefficiently creates an over abundance of secondary heat. Fluorescent lighting that is moderately priced lasts 5000-8000 hours (4 times longer than incandescent). This type of lighting is available in warm and cold varieties and is ~4 times more efficient than incandescent. Fluorescent lights do not operate well at low temperatures and must come up to operating temperatures before maximum light output. Mercury is a concern when disposing of these bulbs, and they tend to heat up when lit for a time. Light Emitting Diode lighting is rather expensive but last upwards of 50,000 to even 100,000 hours. LEDs are moisture, vibration and shock resistant, and instantly obtain maximum output. Most LED lights produce a low lumen for their respective size. LED light bulbs are true watt misers being ~ 20 times more efficient than incandescent, and they remain very cool to the touch. Like fluorescent lights, different color temperatures are available for warm or cool lighting. LEDs also come in many color varieties.

Table 2. 5 Energy Efficiency and Energy costs of Light emitting diodes, Incandescent and the fluorescent lighting [28]

<table>
<thead>
<tr>
<th>Energy efficiency &amp; Energy Costs</th>
<th>Light Emitting Diodes Luminaires</th>
<th>Incandescent Light Bulbs</th>
<th>Compact Fluorescents Bulbs</th>
</tr>
</thead>
<tbody>
<tr>
<td>Life Span (average)</td>
<td>50 K hours</td>
<td>1,200 hours</td>
<td>8,000 hours</td>
</tr>
<tr>
<td>Watts of electricity used (equivalent to 60 watt bulb).</td>
<td>6 - 8 watts</td>
<td>60 watts</td>
<td>13-15 watts</td>
</tr>
<tr>
<td>Kilo-watts of Electricity used</td>
<td>329 KWh/yr.</td>
<td>3285 KWh/yr.</td>
<td>767 KWh/yr.</td>
</tr>
</tbody>
</table>
Table 2. Light output for Different lighting systems (LED, Incandescent and CFLs) [28]

<table>
<thead>
<tr>
<th>Light output (Lumens)</th>
<th>Light Emitting Diode Luminaires(LEDs) (Watts)</th>
<th>Incandescent Light Bulbs (Watts)</th>
<th>Compact Fluorescents (Watts)</th>
</tr>
</thead>
<tbody>
<tr>
<td>450</td>
<td>4-5</td>
<td>40</td>
<td>9-13</td>
</tr>
<tr>
<td>800</td>
<td>6-8</td>
<td>60</td>
<td>13-15</td>
</tr>
<tr>
<td>1,100</td>
<td>9-13</td>
<td>75</td>
<td>18-25</td>
</tr>
<tr>
<td>1,600</td>
<td>16-20</td>
<td>100</td>
<td>23-30</td>
</tr>
<tr>
<td>2,600</td>
<td>25-28</td>
<td>150</td>
<td>30-55</td>
</tr>
</tbody>
</table>
CHAPTER 3
EXPERIMENTAL SETUP

In this chapter, with a detailed description of the experimental setup built for studying the effect of vibrations on LED luminaires and CFLs is presented. The set-up includes a vibration table, goniometer, spectrometer and the associated software. Experimental procedure including conversions, errors and corrections are also presented in this chapter.

3.1 Experimental setup

The hardware experimental setup consists of four main components, a vibration table, a goniometer, lamp fixture and spectrometer along with its optics. In addition, there is spectrometer specific software. Details of each of these components are described below.

3.1.1 Vibration table

The model 113 ELECTRO-SEIS shaker is fundamentally a force generator. Its basic operating principle is the magneto static force, Lorentz force. When a current carrying conductor is placed in a dc magnetic field perpendicular to the direction of the current, the plate experiences the Lorenz force acting on the electrons in a direction perpendicular to the both the current and the magnetic field (given by the right hand rule) [29]. A schematic illustration of the Lorentz force is presented in Figure 3.1.
Figure 3.1 A Schematic diagram illustrating the principle of electro-dynamic force generation

N and S poles of the magnet creating flux density, B, in air gap. Force, F, acts on the conductor carrying current, I. The magnitude of the generated force is directly proportional to the instantaneous value of current and the magnetic flux density and the force is in a direction mutually perpendicular to the directions of both current and magnetic field [29]. Corresponding to the force generated on the current carrying conductor and associated armature structure, there is an equal and oppositely directed reaction force, F, developed on the magnetic field structure or body of the shaker. Thus the shaker table platform moves by Newton’s third law. Since the force generated directly relates to the current and its time dependence, the Model 113 shaker is capable of generating anytime waveform of force in accordance with an identical time waveform of current supplied to it. Thus, the magnitude and the waveform are directly adjustable by the user as needed. A photograph of the Model 113 Shaker used as a vibration table is shown in Figure 3.2.
3.1.2 Maximum Force and Current ratings

The continuous duty force rating of the model 113 dictated by the maximum allowable temperature rise of the natural convection-cooled armature coil. This establishes maximum allowed electrical power dissipation and corresponding force and nominal current limits of 21.2 lb, 94N rms and 3.54A rms, respectively. Therefore, for continuous sinusoidal operation above 0.1 HZ, the maximum ratings are 30 lb, 133N vector. For sinusoidal operation between dc and 0.1 Hz, where the period of the current waveform is long when compared to the thermal time constant of the armature coil, the
maximum ratings are 21.2 lb, 94N vector and 3.54A vector (0.707 times the higher frequency values). Above 20 Hz, because of an increasing voltage requirement, maximum force is limited to less than 30lb, 133N vector depending on the amplifier capability [29]. The Figure 3.3 describes how the acceleration varies with different frequency with various mass loads. The maximum acceleration is between 10 – 25Hz at no load condition.

![Acceleration with Various Mass Loads](image)

Figure 3.3 Acceleration of various mass loads versus different frequencies

3.1.3 Maximum stroke

Many building and rig structures have resonance frequencies, which lie in the range of 1 to 20Hz. Their resonance frequencies are low by the virtue of their large dimensions and/or corresponding low stiffness/mass ratio. While vibrating at resonance, the antinodes or points of maximum deflection on such structures can execute displacements
of the order of an inch or more, and yet the stresses remain well below the elastic limit.
The shaker has a 6.25-in (15.9-cm) peak-to-peak relative stroke capability [29].

3.1.4 Amplifier

The model APS 144 Dual-mode power amplifier designed to provide drive power for
shaker 113. The amplifier has features, which make it particularly useful for studying the
dynamic characteristics of structures. The Dual-mode amplifier allows operating in either
a voltage or current amplifier mode. In this study, the amplifier operated in the voltage
mode. This mode produces an approximate “constant velocity” response as a function of
frequency in the region of armature suspension resonance. This mode produces high
internal damping in the shaker armature motion due to the low amplifier source
impedance. For required mode of operation for the shaker, the amplifier switched to
Current mode.

3.1.5 Frequency generator

A frequency generator is used to adjust the frequencies and the amplitudes to desired
value manually. A photograph of the frequency generator is shown in Figure 3.4. The
frequency range used is 5 to 15 Hz. A frequency versus amplitude plot generated using
the frequency generator along with the shaker table is shown in Figure 3.5. It is clear that
the shaker table acts as a low pass filter with a bandwidth of about 12 Hz, the amplitude
drops off drastically.

Figure 3.4 A photograph of the Function generator
3.2 Lamp fixture and the bulb

A standard lamp fixture for PAR30 and two types of CFL bulbs fixed to the movable platform of the vibration table (Figure 3.6). The lamp fixture fixed rigidly to the platform so that the fixture and the lamp move together with no relative motion between them along with the platform. The PAR 30 LED luminaires used are rated 14W and produce 720 lumen with an estimated life of 40,000 hours. The CFL bulbs used are rated 15W and produce 550 lumens with an estimated life of 5000 hours. The CFL (Ecosmart) bulbs are rated 15W and produce 1500 lumens with an estimated life of 6000 hours.
Figure 3.6 (a) A photograph of the complete experimental setup (b) A closer look of a lamp fixture fixed to the movable platform of the vibration table.
Table 3.1 Comparison of costs savings on the bulbs used in this work and normal incandescent bulb

<table>
<thead>
<tr>
<th></th>
<th>Incandescent</th>
<th>CFL</th>
<th>LED</th>
</tr>
</thead>
<tbody>
<tr>
<td>Life Span (in hours)</td>
<td>1,500</td>
<td>5,500</td>
<td>40,000</td>
</tr>
<tr>
<td>Watts</td>
<td>60</td>
<td>15</td>
<td>14</td>
</tr>
<tr>
<td>Cost</td>
<td>$1.345</td>
<td>$6.00</td>
<td>$54.95</td>
</tr>
<tr>
<td>KWH of electricity used over 40k hours</td>
<td>2,400</td>
<td>600</td>
<td>560</td>
</tr>
<tr>
<td>Electricity Cost (@ $0.10 per KWh)</td>
<td>$240.00</td>
<td>$60.00</td>
<td>$56.00</td>
</tr>
<tr>
<td>Bulbs needed for 40k hours of usage</td>
<td>26</td>
<td>7</td>
<td>1</td>
</tr>
<tr>
<td>Equivalent 40k hour bulb expense</td>
<td>$34.97</td>
<td>$42.00</td>
<td>$54.95</td>
</tr>
<tr>
<td><strong>Total 60,000 Hour Lighting Spend</strong></td>
<td><strong>$274.97</strong></td>
<td><strong>$102.00</strong></td>
<td><strong>$110.95</strong></td>
</tr>
</tbody>
</table>

Calculate Your Energy Savings

# of household light bulbs | 30 | 30 | 30
Your estimated daily usage (hours) | 5 | 5 | 5
Days in month | 30 | 30 | 30

Household savings over 40,000 hours (energy + replacement)

<table>
<thead>
<tr>
<th></th>
<th>Incandescent</th>
<th>CFL</th>
<th>LED</th>
</tr>
</thead>
<tbody>
<tr>
<td>Household cost</td>
<td>$8,249.10</td>
<td>$3,060.00</td>
<td>$3,328.50</td>
</tr>
<tr>
<td>Savings by switching from Incandescent</td>
<td>$0.00</td>
<td>$5,189.10</td>
<td>$4,920.60</td>
</tr>
</tbody>
</table>

Monthly household energy savings

<table>
<thead>
<tr>
<th></th>
<th>Incandescent</th>
<th>CFL</th>
<th>LED</th>
</tr>
</thead>
<tbody>
<tr>
<td>KWH used per month</td>
<td>270</td>
<td>68</td>
<td>63</td>
</tr>
<tr>
<td>Electricity Cost (@ $0.10 per KWh)</td>
<td>$27.00</td>
<td>$6.75</td>
<td>$6.30</td>
</tr>
<tr>
<td>Savings by switching from Incandescent</td>
<td>$0.00</td>
<td>$20.25</td>
<td>$20.70</td>
</tr>
</tbody>
</table>

Yearly household energy savings

<table>
<thead>
<tr>
<th></th>
<th>Incandescent</th>
<th>CFL</th>
<th>LED</th>
</tr>
</thead>
<tbody>
<tr>
<td>KWH used per year</td>
<td>3,285</td>
<td>821</td>
<td>767</td>
</tr>
<tr>
<td>Electricity Cost (@ $0.10 per KWh)</td>
<td>$328.50</td>
<td>$82.13</td>
<td>$76.65</td>
</tr>
<tr>
<td>Projected savings by switching from Incandescent</td>
<td>$0.00</td>
<td>$246.38</td>
<td>$251.85</td>
</tr>
</tbody>
</table>

3.3 Goniometer

A goniometer is an instrument that either measures angle or allows an object to rotate to a precise angular position. A goniometer constructed for the purpose of this
study with a view to collect spatial spectral emission data of the tested light sources. A photograph of the goniometer is shown in Figure 3.6. The goniometer has three degrees of freedom, radially from a fixed center (44.74”), horizontally (11”) and angularly (-90° to 90°). Thus, the goniometer is able to cover considerable spatial area around the lamp fixture for the study of spatial variation of the light emission. The range of angles for the goniometer used is 55° to 125°. The maximum distance from the source is 44.74”. Angles are set and measured with the help of a protractor placed on the setup (Figure 3.6). The lengths measured with a resolution of 1/8 inch using the graduations made on the ruler. All the dimensions of the experimental setup is shown in Figure 3.7.

Figure 3.7 A schematic diagram with experimental setup with dimensions
3.4 Spectrometer

An Ocean Optics USB4000 Miniature Fiber Optic Spectrometer is shown in Figure 3.7 and 3.7(a) is used. This modular spectrometer is responsive in the range of 200-1100nm [30]. The USB4000 Spectrometer is distinguished by its enhanced electronics has 16-bit A/D resolution for auto nulling, EEPROM storage of calibration coefficients for simple spectrometer start-up, Eight programmable GPIO signals for controlling peripheral devices, and an electronic shutter for spectrometer, whose integration time is as fast as 3.8 microseconds. The USB4000 has signal-to-noise of 300:1, sensitivity of 130 photons/count at 400nm, and optical resolution (FWHM) ranging from 0.3-10.0nm [30].

Figure 3. 8 A schematic figure showing spectrometer and its parts

(1)SMA 905 Connector (2) Fixed Entrance Slit (3) Long pass Absorbing Filter (4&6) Collimating& Focusing Mirrors (5) Choosing a Grating & Wavelength Range (7) L2& L4 Detector Collection Lens (8) Detector: 2048- or 3648-element Linear CCD Array. (9) Detector with OFLV Filter (10) Detector with UV2 or UV4 Detector Window Upgrade.
SMA 905 Connector (1) aligns to the spectrometer’s entrance slit and ensures concentricity of the fiber. Fixed Entrance Slit (2) are rectangular apertures, 1-mm tall and various widths from 5 µm to 200 µm [30]. The width determines the amount of light entering the bench. The smallest slit achieves the best optical resolution. Long pass Absorbing Filter (3) have a transmission band and a blocking band to restrict radiation to a certain wavelength region for eliminating second- and third-order effects. These filters installed permanently between the slit and the clad mode aperture in the bulkhead of the Connector. Collimating& focusing mirrors (4&6) are standard aluminum-coated reflective mirrors are replaced with UV-absorbing SAG+ mirrors. They increase reflectance in the VIS-NIR and, in turn, increase the sensitivity of the spectrometer. These mirrors also absorb nearly all UV light, which reduces the effects of excitation scattering in fluorescence measurements. Unlike typical silver-coated mirrors, the SAG+ mirrors will not oxidize. They have excellent reflectivity, more than 95% across the VIS-NIR [30]. Choosing a Grating & Wavelength Range (5) with each grating, we consider its groove density (which helps determine the resolution), its spectral range (which helps determine the wavelength range) and its blaze wavelength (which helps determine the
most efficient ranges. Detector Collection Lens (7) increases light-collection efficiency and reduces stray light. It is also useful in a configuration with a large-diameter fiber for low light-level applications. 2048- or 3648-element Linear CCD Array detector (8) has an electronic shutter that prevents the detector from saturating and makes possible analysis of transient events such as laser pulses [30]. A charge-coupled device (CCD) is an analog shift register that enables the transportation of analog signals (electric charges) through successive stages (capacitors), controlled by a clock signal. Detectors with OFLV Filters (9) applied to the detector’s window to eliminate second- and third-order effects. Detector with UV2 or UV4 detector window upgrade (10) replaces the detector’s standard BK7 window with a quartz window to enhance the spectrometer's performance from 200-340 nm. The UV4 is available in the USB4000 Optical Bench [30].

There are three sets of experiment which are followed for all the lamps

Experiment 1
Lamps are subjected to vibrations for 24-hours and when the vibrations are stopped the intensity measurements are taken.

Experiment 2
Lamps are subjected to vibrations for 10 minutes for every single frequency and intensity measurements are taken after the vibrations are stopped.

Experiment 3
Test for effect of temperature over time. The intensity values are measured for every 5 minutes at every single frequency with no vibrations.
3.4.1 Spectrometric measurements

Using the spectrometer, the spectrum, (intensity and wavelength) relations are measured and compared with that of the LS-1-CAL calibration supplied with the instrument. Spectra suite software is employed to obtain the Intensity in counts versus the wavelength in Nanometers (nm) on Y and X-axis respectively.

3.4.2 Measurements calibration and Calculations

The measurements for two different types of lamps, the PAR 30 bulbs and the CFLs are conducted. The intensities were measured at various angles (α) and three different distances i.e. 30.74, 34.74, 39.74 inches as shown in Figure 3.6. Errors in intensities resulting from measuring angles and lengths found to be very small and hence neglected. All the lamps are subjected to vibrations for 24-hours.

3.4.2.1 Measured and actual intensities

As shown in Figure 3.8, the spectrometer is not oriented directly towards the light fixture. The line connecting light source and the spectrometer makes an angle of θ with the direction at which the spectrometer points. Thus, the spectrometer captures only \( \cos\theta \) fraction of the total intensity due to the source at the spectrometer. Thus, the measured intensity divided by \( \cos\theta \) as shown

\[
I_{\text{actual}} = \frac{I_{\text{measured}}}{\cos\theta},
\]

where, \( I_{\text{actual}} \) and \( I_{\text{measured}} \) are the actual and measured intensities, respectively.
3.4.2.2 Measured and actual distances

The intensities were measured at various angles (\( \alpha \) in the range of -35° to 35°) and three different distances i.e. 30.74, 34.74 and 39.74 inches as shown in Figure 3.6. For our setup, there are two known lengths, measured manually. As shown in Figure 3.8 we know lengths L1 and L2. L1 is the vertical distance from the axis of the fixed rod to the centre of the lamp and L2 is the distance from the axis (O) location where the spectrometer is attached. \( \alpha \) is the angle between the L1 and L2. We calculated \( \theta \) from the below formulae.
According to the law of sine’s, \( L_1, L_2, r, \alpha, \beta \) and \( \theta \) are related as:

\[
\frac{L_1}{\sin \theta} = \frac{L_2}{\sin \beta} = \frac{r}{\sin \alpha}
\]

According to the law of cosines,

\[
L_1^2 = (L_2)^2 + r^2 - 2(L_2) (r) \cos \theta
\]

\[
L_2^2 = (L_1)^2 + r^2 - 2(L_1) (r) \cos \beta
\]

\[
r^2 = (L_1)^2 + (L_2)^2 - 2(L_2) (L_1) (r) \cos \alpha
\]

![Figure 3.11 A schematic drawing showing how to calculate \( \cos \theta \)](image)

3.4.2.3 Intensity conversions from counts to \( \mu \text{W/cm}^2/\text{nm} \)

The intensities measured in counts. The intensities were converted using the standard calibration meter named LS-1-CAL, using which measurements of intensities in counts can be converted into \( \mu \text{W/cm}^2/\text{nm} \). With the calibration source LS-1-CAL intensities are measured in both counts and in the absolute terms in \( \mu \text{W/cm}^2/\text{nm} \) and the inverse ratio of these quantities is obtained multiplying the intensity values from measurement in counts.
3.4.2.4 Intensity of light as perceived by humans in lumens

Intensities in $\mu$W/cm$^2$/nm measured using the spectrometer, are not standardized with the human eye response, i.e., the intensities of various wavelengths of light perceived by human eye is not the same the spectrometer measurements. The human eye response is different for different wavelengths as shown Figure 3.10. Finally, we get the units of Intensities in Lumen/cm$^2$ with the help of normalization. Now to convert these intensities (Lumen/cm$^2$) into lumen values we need to calculate the Intensities of particular angles at particular points.

**Standard eye sensitivity**

![Standard eye sensitivity diagram](image)

Figure 3.12 Response of human eye to light.
CHAPTER 4

RESULTS AND DISCUSSION

In this chapter, results and discussion are presented. The measurements intensities as a function of wavelengths of three different lamps LED luminaires, CFL (NUVUE) CFL (Ecostar) at various lengths and angles are shown, compared and contrasted for various vibration conditions (no vibration, 5Hz, 10Hz and 15Hz). Additionally variety different vibrational experiments were conducted on CFLs and results are reported and discussed.

4.1 Spectrometric Measurements

Using the spectrometer Ocean optics USB 4000, from the spectrum, representing the wavelengths and intensities (counts) for particular wavelengths, i.e., 440, 460, 495, 550, 600 and 680nm respectively were measured at three different distances from the source 0.77807 m (30.74 inches), 0.882 m (34.74 inches) and 1m (39.74 inches)

4.2 LED luminaires measurement

In this work a High Power PAR30 26 Degree LED luminary- Warm White lamps is used. A photograph of the lamp is shown in Figure 4.1. Manufacturer’s specifications for the lamp are presented in Table 4.1

<table>
<thead>
<tr>
<th>Color</th>
<th>Wattage</th>
<th>Hours</th>
<th>Base</th>
<th>Voltage(V)</th>
<th>Lumens(lm)</th>
<th>CCT (K)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Warm white</td>
<td>14W</td>
<td>50,000</td>
<td>E26</td>
<td>110-130V</td>
<td>596</td>
<td>2500-3200K</td>
</tr>
</tbody>
</table>
Experiment 1 where lamps are subjected to vibrations for 24-hours and when the vibrations are stopped the intensity measurements are taken. Plots of intensity (counts) versus angles (degrees) for various wavelengths at a distance of 30.74” from the axis are shown in Figures 4.2(a) and 4.2(b), for the case of before vibration and after 5Hz vibration for 24 hours. For all wavelengths, the peak intensity increased by 15% with vibrations. Additionally, the area under the curve that is directly to the lumens also increased by about 16% which is approximately evaluated using the intensity versus angle curve for 600nm. This method of approximately evaluating the lumens is adopted and used for all measurements.

Figure 4.1 A photograph of High Power PAR30 26 Degree LED - Warm White
Figure 4.2 Intensity versus angle at a distance of 30.74 inches from the source for various wavelengths (a) before vibrations (b) after vibrations at 5Hz for 24 hours.
Plots of intensity (counts) versus angles (degrees) for various wavelengths at a distance of 34.74 inches from the axis are shown in Figures 4.3(a) and 4.3(b), for the case of before vibration and after 5Hz vibration for 24 hours. For all wavelengths, the peak intensity decreased by 11% with vibrations. Additionally, the area under the curve that is directly to the lumens also decreased by about 9%.
Figure 4.3 Intensity versus angle at a distance of 34.74 inches from the source for various wavelengths (a) before vibrations (b) after vibrations at 5Hz for 24 hours.

Plots of intensity (counts) versus angles (degrees) for various wavelengths at a distance of 39.74 inches from the axis are shown in Figures 4.4(a) and 4.4(b), for the case of before vibration and after 5Hz vibration for 24 hours. For all wavelengths, the peak intensity decreased by 9% with vibrations. Additionally, the area under the curve that is directly to the lumens also decreased by about 10%.
Figure 4. 4 Intensity versus angle at a distance of 39.74 inches from the source for various wavelengths (a) before vibrations (b) after vibrations at 5Hz for 24 hours.
Plots of intensity (counts) versus angles (degrees) for various wavelengths at a distance of 30.74 inches from the axis are shown in Figures 4.5(a) and 4.5(b), for the case of before vibration and after 10Hz vibration for 24 hours. For higher wavelengths, i.e., 600nm and 550nm, the peak intensity increased by 3% with vibrations and for all other wavelengths there is no effect due to vibrations. Additionally, the area under the curve that is directly to the lumens also increased by about 6% With vibrations, peak intensity is shifted by 5º angle, which may be related to the orientation shift of the fixture/lamp assembly.
Figure 4.5 Intensity versus angle at a distance of 30.74 inches from the source for various wavelengths (a) before vibrations (b) after vibrations at 10Hz for 24 hours.

Plots of intensity (counts) versus angles (degrees) for various wavelengths at a distance of 34.74 inches from the axis are shown in Figures 4.6(a) and 4.6(b), for the case of before vibration and after 10Hz vibration for 24 hours. For higher wavelengths i.e., 600nm and 550nm, the peak intensity decreased by 15% with vibrations and for all other wavelengths there is no effect due to vibrations. The area under the curve that is directly to the lumens also increased by about 16%.
Figure 4. 6 Intensity versus angle at a distance of 34.74 inches from the source for various wavelengths (a) before vibrations (b) after vibrations at 10Hz for 24 hours.
Plots of intensity (counts) versus angles (degrees) for various wavelengths at a distance of 39.74 inches from the axis are shown in Figures 4.7(a) and 4.7(b), for the case of before vibration and after 10Hz vibration for 24 hours. For higher wavelengths i.e., 600nm and 550nm, the peak intensity decreased by 6% with vibrations and for all other wavelengths there is no effect due to vibrations. Additionally, the area under the curve that is directly to the lumens decreased by about 2%.

![Intensity vs Angle (39.74 inches)](image-url)
Figure 4.7 Intensity versus angle at a distance of 39.74 inches from the source for various wavelengths (a) before vibrations (b) after vibrations at 10Hz for 24 hours.

Plots of intensity (counts) versus angles (degrees) for various wavelengths at a distance of 30.74 inches from the axis are shown in Figures 4.8(a) and 4.8(b), for the case of before vibration and after 15Hz vibration for 24 hours. For all the wavelengths, the peak intensity increased by 5% with vibrations, at 495nm the peak decreases by 40%. Additionally, the area under the curve that is directly to the lumens also increased about 5%.
Figure 4. 8 Intensity versus angle at a distance of 30.74 inches from the source for various wavelengths (a) before vibrations (b) after vibrations at 15Hz for 24 hours.
Plots of intensity (counts) versus angles (degrees) for various wavelengths at a distance of 34.74 inches from the axis are shown in Figures 4.9(a) and 4.9(b), for the case of before vibration and after 15Hz vibration for 24 hours. For 600nm the peak intensity decreased by 25% and all other wavelengths the peak intensity decreased by 15% with vibrations. The area under the curve that is directly to the lumens decreased by about 26%.
Figure 4.9 Intensity versus angle at a distance of 34.74 inches from the source for various wavelengths (a) before vibrations (b) after vibrations at 15Hz for 24 hours.

Plots of intensity (counts) versus angles (degrees) for various wavelengths at a distance of 39.74 inches from the axis are shown in Figures 4.10(a) and 4.10(b), for the case of before vibration and after 15Hz vibration for 24 hours. For all the wavelengths the peak intensity and the area under the curve there is no effect due to vibrations.
Figure 4. 10 Intensity versus angle at a distance of 39.74 inches from the source for various wavelengths (a) before vibrations (b) after vibrations at 15Hz for 24 hours.
4.2.1 Intensity Measurements with varying vibrational frequencies

Experiment 2 where lamps are subjected to vibrations for 10 minutes for every single frequency and intensity measurements are taken after the vibrations are stopped. Intensity measurements of 546.78 nm at varying vibrational frequencies show that vibration has serious detrimental effects on the performance, i.e., there is either an increase and/or a decrease in intensities. There is no consistent pattern in the variation of the peak intensities. The intensity range is 53000-62000 counts for a frequency range of 1-50Hz.

Figure 4.11 A plot of frequency versus intensity at 546.78nm
4.2.2 Summary and discussion on LED luminaires measurements

The following is the summary of observations of measurements of LED luminaires.

• In general, 24-hour vibration effects the intensity distribution.

• Vibration measurements at a distance of 34.74 inches and 39.74 inches show a decrease in peak intensity, whereas 30.74 inches measurements show an increase.

• A maximum of 15% increase in peak intensity is observed for 5Hz vibration at 30.74 inches and maximum decrement in peak intensity of 25% due to vibration is observed for 10Hz at 34.74 inches.

• Intensity measurements of 546.78 nm at varying vibrational frequencies (at 1Hz increment, measurements at each frequency for 10 minutes) show that vibration has serious detrimental effects on the performance. The lamp shows no consistency in the variation of peak intensities.

4.3 CFL measurements

To compare the LED luminaires measurement against that of CFL of comparable lumen, two CFLs were chosen – CFL (Nuvue) and CFL (Ecosmart). Vibrational results pertaining to these are presented and discussed in this section.

4.3.1 CFL (Nuvue) measurements

In this work a Compact Fluorescent bulb R30 bulb - Warm White lamps is used. A photograph of the lamp is shown in Figure 4.11. Manufacturer’s specifications for the lamp are shown in Table 4.2.
Table 4.2 Manufacturer’s Specifications [1]

<table>
<thead>
<tr>
<th>Color</th>
<th>Wattage</th>
<th>Hours</th>
<th>Base</th>
<th>Voltage(V)</th>
<th>Lumens(lm)</th>
<th>CCT (K)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Warm white</td>
<td>15W</td>
<td>6,000</td>
<td>E26</td>
<td>120V</td>
<td>550</td>
<td>2700K</td>
</tr>
</tbody>
</table>

Figure 4. 12 A photograph of Compact Fluorescent bulb R30 bulb - Warm White

Experiment 1 where lamps are subjected to vibrations for 24-hours and when the vibrations are stopped the intensity measurements are taken. Plots of intensity (counts) versus angles (degrees) for various wavelengths at a distance of 30.74 inches from the axis are shown in Figures 4.13(a) and 4.13(b), for the case of before vibration and after 5Hz vibration for 24 hours. For all the wavelengths, the vibrations did not affect the peak intensity and the area under the curve that is directly to the lumens, is unaffected.
Figure 4. Intensity versus angle at a distance of 30.74 inches from the source for various wavelengths (a) before vibrations (b) after vibrations at 5Hz for 24 hours.
Plots of intensity (counts) versus angles (degrees) for various wavelengths at a distance of 34.74 inches from the axis are shown in Figures 4.14(a) and 4.14(b), for the case of before vibration and after 5Hz vibration for 24 hours. For all the wavelengths, the vibrations did not affect the peak intensity and the area under the curve that is directly to the lumens is unaffected.
Figure 4. 14 Intensity versus angle at a distance of 34.74 inches from the source for various wavelengths (a) before vibrations (b) after vibrations at 5Hz for 24 hours.

Plots of intensity (counts) versus angles (degrees) for various wavelengths at a distance of 39.74 inches from the axis shown in Figures 4.15(a) and 4.15(b), for the case of before vibration and after 15Hz vibration for 24 hours. For all the wavelengths, the vibrations did not affect the peak intensity and the area under the curve that is directly to the lumens is unaffected.
Figure 4. 15 Intensity versus angle at a distance of 39.74 inches from the source for various wavelengths (a) before vibrations (b) after vibrations at 5Hz for 24 hours.
Plots of intensity (counts) versus angles (degrees) for various wavelengths at a distance of 30.74 inches from the axis are shown in Figures 4.16(a) and 4.16(b), for the case of before vibration and after 10Hz vibration for 24 hours. For all the wavelengths the peak intensity creased by 10% with vibrations. The area under the curve that is directly to the lumens has also increased by about 14%. At 550 nm, the peak shifted in angle from 100º to 105º, which may be related to oriental shift of the fixture/lamp assembly.
Figure 4. 16 Intensity versus angle at a distance of 30.74 inches from the source for various wavelengths (a) before vibrations (b) after vibrations at 10Hz for 24 hours.

Plots of intensity (counts) versus angles (degrees) for various wavelengths at a distance of 34.74 inches from the axis are shown in Figures 4.17(a) and 4.17(b), for the case of before vibration and after 10Hz vibration for 24 hours. For 600nm the peak intensity increased by 25% and all other wavelengths the peak intensity increased by 15% with vibrations. The area under the curve that is directly to the lumens also increased by about 58%. The peak also shifted in angle from 95° to 100° for all the wavelengths, which may be related to oriental shift of the fixture/lamp assembly.
Figure 4.17 Intensity versus angle at a distance of 34.74 inches from the source for various wavelengths (a) before vibrations (b) after vibrations at 10Hz for 24 hours.
Plots of intensity (counts) versus angles (degrees) for various wavelengths at a distance of 39.74 inches from the axis are shown in Figures 4.18(a) and 4.18(b), for the case of before vibration and after 10Hz vibration for 24 hours. For 600nm the peak intensity increased by 30% and all other wavelengths the peak intensity increased by 25% with vibrations. The area under the curve that is directly to the lumens also increased by about 42%.
Figure 4.18 Intensity versus angle at a distance of 39.74 inches from the source for various wavelengths (a) before vibrations (b) after vibrations at 10Hz for 24 hours.

Plots of intensity (counts) versus angles (degrees) for various wavelengths at a distance of 30.74 inches from the axis are shown in Figures 4.19(a) and 4.19(b), for the case of before vibration and after 15Hz vibration for 24 hours. For all the wavelengths the peak intensity increased by 21% with vibrations. The area under the curve that is directly to the lumens also increased about 39%.
Figure 4.19 Intensity versus angle at a distance of 30.74 inches from the source for various wavelengths (a) before vibrations (b) after vibrations at 15Hz for 24 hours.
Plots of intensity (counts) versus angles (degrees) for various wavelengths at a distance of 34.74 inches from the axis are shown in Figures 4.20(a) and 4.20(b), for the case of before vibration and after 15Hz vibration for 24 hours. For all the wavelengths the peak intensity increased by 35% with vibrations. The area under the curve that is directly to the lumens also increased by about 40%.

(a)
Figure 4. 20 Intensity versus angle at a distance of 34.74 inches from the source for various wavelengths (a) before vibrations (b) after vibrations at 15Hz for 24 hours.

Plots of intensity (counts) versus angles (degrees) for various wavelengths at a distance of 39.74 inches from the axis are shown in Figures 4.21(a) and 4.21(b), for the case of before vibration and after 15Hz vibration for 24 hours. For 600nm the peak intensity increased by 10% and all other wavelengths the peak intensity was not affected by the vibrations. The area under the curve that is directly to the lumens also increased by about 11%.
Figure 4.21 Intensity versus angle at a distance of 39.74 inches from the source for various wavelengths (a) before vibrations (b) after vibrations at 15Hz for 24 hours.
4.3.1.1 Intensity Measurements with varying vibrational frequencies

Experiment 2 where lamps are subjected to vibrations for 10 minutes for every single frequency and intensity measurements are taken after the vibrations are stopped. Intensity measurements of 546.78 nm at varying vibration frequencies (at 1Hz increment, measurements at each frequency for 10 minutes) show that vibration has serious detrimental effects on the performance. The effect is maximum at 25Hz. For this experiment, the lamp was subjected to vibrations measurements for 10 minutes at every single frequency up to 30Hz at single wavelength, i.e., 546.78 nm. The plot between the frequency and intensity is shown below in Figure 4.22. The intensity is in a range of 53000 – 60000 counts. There is no consistent pattern observable in Figure 4.22 with respect to variation intensities. But, a distinct peak is observed at 26Hz. This effect may be attributable to effective loosening of phosphor coating, which allows more light to escape the glass casing.

Figure 4.22 A plot frequency versus intensity at 546.78nm.
4.3.1.2 Summary and discussion on CFL measurements

The following is the summary of observations of measurements of CFL (Nuvue) lamps.

- In general, 24-hour vibration effects the intensity distribution.
- At 5Hz at 30.74inches and 34.74inches there is no change in intensity whereas, at 39.74 there is increase of 18% of peak intensity.
- At 10Hz at 30.74inches, 34.74inches and 39.74, there is increase in the peak intensity in the range of 10-25%.
- At 15Hz at 30.74inches, 34.74inches and 39.74 there is increase in the range of 10-35% and the area under the curve has increased in the range of 10-40%.
- A maximum of 35% increase in intensity is observed for 15Hz vibration at 34.74 inches.
- Intensity measurements at varying vibrational frequencies (at 1Hz increment, measurements at each frequency for 10 minutes) show that vibration has serious detrimental effects on the performance. A maximum variation is observed at 25Hz.

4.3.2 CFL (Ecosmart) Measurements

In this work a Compact Fluorescent bulb – Soft White lamps are used. A photograph of the lamp is shown in Figure 4.21. Manufacturer’s specifications of the lamp are shown in Table 4.3.

<table>
<thead>
<tr>
<th>Color</th>
<th>Wattage</th>
<th>Hours</th>
<th>Voltage(V)</th>
<th>Lumens(Im)</th>
<th>CCT (K)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Warm white</td>
<td>23W</td>
<td>10,000</td>
<td>120V</td>
<td>1600</td>
<td>2700K</td>
</tr>
</tbody>
</table>
Experiment 1 where lamps are subjected to vibrations for 24-hours and when the vibrations are stopped the intensity measurements are taken. Plots of intensity (counts) versus angles (degrees) for various wavelengths at a distance of 30.74 inches from the axis are shown in Figures 4.24(a), 4.24(b) and 4.24(c), for the case of before vibration, after 5Hz vibration for 24 hours and two days after the vibrations. For 495, 550 and 600nm the peak intensity increased by 5% with vibrations. The area under the curve that is directly to the lumens also increased by about 3% and two days after the vibrations the intensities are same as before the vibrations. The peak also shifted in angle from 95° to 100° for all the wavelengths, which may be related to oriental shift of the fixture/lamp assembly.
Figure 4. 24 Intensity versus angle at a distance of 30.74 inches from the source for various wavelengths (a) before vibrations (b) after vibrations at 5Hz for 24 hours (c) two days after vibrations.

Plots of intensity (counts) versus angles (degrees) for various wavelengths at a distance of 34.74 inches from the axis are shown in Figures 4.25(a), 4.25(b) and 4.25(c), for the case of before vibration, after 5Hz vibration for 24 hours and two days after the vibration. There is no change in peak intensity with vibrations. The area under the curve that is directly to the lumens is unaffected and two days after the vibrations as the intensities are same as they were before the vibrations.
(a)

(b)
Figure 4.25 Intensity versus angle at a distance of 34.74 inches from the source for various wavelengths (a) before vibrations (b) after vibrations at 5Hz for 24 hours (c) two days after vibrations.

Plots of intensity (counts) versus angles (degrees) for various wavelengths at a distance of 39.74 inches from the axis are shown in Figures 4.26(a), 4.26(b) and 4.26(c), for the case of before vibration, after 5Hz vibration for 24 hours and two days after the vibration. There is no change in peak intensity with vibrations. The area under the curve that is directly to the lumens is unaffected and two days after the vibrations as the intensities are same as they were before the vibrations.
Figure 4.26 Intensity versus angle at a distance of 39.74 inches from the source for various wavelengths (a) before vibrations (b) after vibrations at 5Hz for 24 hours (c) two days after vibrations.

Plots of intensity (counts) versus angles (degrees) for various wavelengths at a distance of 30.74 inches from the axis are shown in Figures 4.27(a), 4.27(b) and 4.27(c), for the case of before vibration, after 10Hz vibration for 24 hours and two days after the vibration. There is no change in peak intensity and the area under the curve that is directly to the lumens is unaffected. Two days after the vibrations, the intensities decreased by about 2%. 
Figure 4. 27 Intensity versus angle at a distance of 30.74 inches from the source for various wavelengths (a) before vibrations (b) after vibrations at 10Hz for 24 hours (c) two days after vibrations.

Plots of intensity (counts) versus angles (degrees) for various wavelengths at a distance of 34.74 inches from the axis are shown in Figures 4.28(a), 4.28(b) and 4.28(c), for the case of before vibration, after 10 Hz vibration for 24 hours and two days after the vibration. There is no change in peak intensity with vibrations. The area under the curve that is directly to the lumens is unaffected and two days after the vibrations as the intensities are same as they were before the vibrations.
Figure 4.28 Intensity versus angle at a distance of 34.74 inches from the source for various wavelengths (a) before vibrations (b) after vibrations at 10Hz for 24 hours (c) two days after vibrations.

Plots of intensity (counts) versus angles (degrees) for various wavelengths at a distance of 39.74 inches from the axis are shown in Figures 4.29(a), 4.29(b) and 4.29(c), for the case of before vibration, after 10Hz vibration for 24 hours and two days after the vibration. There is decrement by 10% in peak intensity. The area under the curve that is directly to the lumens decreased to 3% and two days after the vibrations the intensities increased by about 3% when compared with no vibration data.
Figure 4. 29 Intensity versus angle at a distance of 39.74 inches from the source for various wavelengths (a) before vibrations (b) after vibrations at 10Hz for 24 hours (c) two days after vibrations.

Plots of intensity (counts) versus angles (degrees) for various wavelengths at a distance of 30.74 inches from the axis are shown in Figures 4.30(a), 4.30(b) and 4.30(c), for the case of before vibration, after 15Hz vibration for 24 hours and two days after the vibration. There is increment of 8% in peak intensity. The area under the curve that is directly to the lumens also increased by about 6% and two days after the vibrations, the intensities are same as no vibration data. The peak shifted in angle from 95º to 90º two days after the vibrations for all the wavelengths, which may be related to oriental shift of the fixture/lamp assembly.
Figure 4. 30 Intensity versus angle at a distance of 30.74 inches from the source for various wavelengths (a) before vibrations (b) after vibrations at 15Hz for 24 hours (c) two days after vibrations.

Plots of intensity (counts) versus angles (degrees) for various wavelengths at a distance of 34.74 inches from the axis are shown in Figures 4.31(a), 4.31(b) and 4.31(c), for the case of before vibration, after 15Hz vibration for 24 hours and two days after the vibration. There is increment by 10% in peak intensity and decreases by 10% when compared to no vibration data. The area under the curve that is directly to the lumens increased by about 5% and two days after the vibrations the area under the curve decreased by about 8% when compared with no vibration data. The peak shifted in angle from 95° to 85° two days after the vibrations for all the wavelengths, which may be related to oriental shift of the fixture/lamp assembly.
(a)

(b)
Figure 4. 31 Intensity versus angle at a distance of 34.74 inches from the source for various wavelengths (a) before vibrations (b) after vibrations at 15Hz for 24 hours (c) two days after vibrations.

Plots of intensity (counts) versus angles (degrees) for various wavelengths at a distance of 39.74 inches from the axis are shown in Figures 4.32(a), 4.32(b) and 4.32(c), for the case of before vibration, after 15Hz vibration for 24 hours and two days after the vibration. There is increment in peak intensity by 8% after the vibrations, whereas two days after the vibrations the intensities increase by about 3% more when compared to no vibration data. The area under the curve that is directly to the lumens decreased by about 3% which is approximated with 550nm peak curve and two days after the vibrations the area under the curve is decreased by 5% more when compared with data before the vibrations.
Figure 4.32 Intensity versus angle at a distance of 39.74 inches from the source for various wavelengths (a) before vibrations (b) after vibrations at 15Hz for 24 hours (c) two days after vibrations.

4.3.2.1 Intensity Measurements with varying vibrational frequencies

Experiment 2 where lamps are subjected to vibrations for 10 minutes for every single frequency and intensity measurements are taken after the vibrations are stopped. Intensity measurements at varying vibrational frequencies show that vibration has serious detrimental effects on the performance. The effect is maximum at 26Hz, which is close value to the CFL (Nuvue). This shows that the CFLs are affected at 25-26Hz frequency. The measurements were taken at 546.78nm. The intensity is in a range of 53000 – 60000 (counts). A plot of Intensity versus vibrational frequency is shown in Figure 4.33.
4.3.2.2 Long term no vibration test

Experiment 3 is the test for effect of temperature over time. The intensity values are measured for every 5 minutes at every single frequency with no vibrations. In order to understand the effect of heating on intensity variation and hence to decouple the effect from vibrations, a CFL (ecosmart) lamp was subjected to experiments without vibrations. The lamp was turned on and intensity measurements of 546.78 nm corresponding to its peak with respect to angle were taken every 10 minutes. A plot of peak intensity versus time is shown in Figure 4.34. The data shows that heating does affect the peak intensity by about 2% over 4 hours. Thus, the heating over many hours may partially account for the intensity variations, but not entirely. This effect especially does not account for increases in intensity.
4.3.2.3 Summary and discussion on CFL (Ecosmart) measurements

The following is the summary of observations of measurements of CFL lamps.

- In general, 24-hour vibration effects the intensity distribution.
- Vibration measurements at all the distances of show a change in intensity, which is very difficult to explain.
- At 5Hz at 30.74 inches, there is an increase in peak intensity whereas, at 34.74 inches and 39.74 inches there is no change.
- A maximum of 10% increase in peak intensity is observed for 15Hz vibration at 34.74 inches and a maximum decrement due to vibration is observed for 10Hz at 39.74 inches.
- In case of 15Hz, two days after the vibration, the peak intensity is lower than that for the case with no vibration.
• Intensity measurements of 546.78 nm at varying vibrational frequencies (at 2Hz increment, measurements at each frequency for 10 minutes) show that vibration has serious detrimental effects on the performance. Intensity is in a range of 53000-60000 (counts). The effect is maximum at 26Hz.

4.5 Discussion

In general, all lamps show change in light intensity distribution with vibration. The change in intensity distribution is not consistent, i.e., always increase and decrease. In most cases, the vibrations result in increase in intensity distribution and lumens. The effect of vibrations is more on the CFLs compared to the LED luminaires. The effect of vibration on the CFL can be related to falling off the phosphor coatings on the inner wall of the CFL. Same effect on the LED luminaire is minimal because the phosphor distribution is unaffected as it is sandwiched between the active area and the epoxy lens. Subjecting the lamps to varying vibrational frequencies over time makes all lamps degrade in performance with a wide variation in peak intensities. CFL (Ecosmart) performed the best of all three luminaires. LED was comparable to CFL (Ecosmart) and CFL (NUVUE) was the worst.

This study has identified that the mechanical vibrations in the frequency range of 0-30Hz that is typical in buildings and oilrigs due to heating, ventilation, air-conditioning systems (HVAC), has a serious effect on LED and CFL luminaires. This work is preliminary and more thorough and systematic study is warranted to make definite conclusions and hence possible technological recommendations.
CHAPTER 5
CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

All the measurements summarized in Table 5.1 shown below.

Table 5.1 Summary of all the lamps at various angles and distances in different vibrational conditions

<table>
<thead>
<tr>
<th>Frequency (Hz)</th>
<th>Lamp types</th>
<th>30.74 inches</th>
<th>34.74 inches</th>
<th>39.74 inches</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Intensity (%)</td>
<td>Lumen (%)</td>
<td>Intensity (%)</td>
<td>Lumen (%)</td>
</tr>
<tr>
<td>5</td>
<td>LED</td>
<td>+15</td>
<td>+16</td>
<td>+11</td>
</tr>
<tr>
<td></td>
<td>CFL(N)</td>
<td>NC</td>
<td>NC</td>
<td>NC</td>
</tr>
<tr>
<td></td>
<td>CFL(E)</td>
<td>+5</td>
<td>+5</td>
<td>NC</td>
</tr>
<tr>
<td>10</td>
<td>LED</td>
<td>+3</td>
<td>+6</td>
<td>-15</td>
</tr>
<tr>
<td></td>
<td>CFL(N)</td>
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<td>+25</td>
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</tr>
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<td>CFL(N)</td>
<td>+21</td>
<td>+39</td>
<td>+35</td>
</tr>
<tr>
<td></td>
<td>CFL(E)</td>
<td>+8</td>
<td>+6</td>
<td>+10</td>
</tr>
</tbody>
</table>

- Intensity and Lumen are the percentage change from no vibration to the vibration data.
- LED- Light Emitting Diode Luminaire.
• CFL (N) – Compact Fluorescent Lamp (Nuvue).
• CFL (E) – Compact Fluorescent Lamp (Ecosmart).
• NC – No Change.

In this work, a LED and two types of Compact fluorescent lamps were investigated for the intensity variation due to mechanical vibrations in the range of 0 to 30 HZ. In general, subjecting the lamps to 24-hour vibration affects the total intensity percentage variations of peak intensities after vibrations is in the range of -25 to +15% compared to those of no vibrations for the light emitting diode luminaires. For the case of compact fluorescent lamps (Nuvue) the variations are in range from +10 to +35%, whereas for the Compact fluorescent lamps (Ecosmart) the intensity peaks range from -10 to +10%. Continuous vibration measurements at varying vibrational frequencies, i.e., measurements at each frequency for every 10 minutes show that in the case of LED luminaires, there is no consistency of intensity peaks, i.e. there is an increase and decrease in intensities. In the case of both compact fluorescent bulbs, there is an increase in intensity at the wavelength of 546.78nm (wavelength of maximum human sensitivity) which reaches a maximum at around 25Hz. Intensity variation effects due to vibration are attributed to the dropping off loose phosphor coatings in the inside wall of the glass enclosures. This effect is more pronounced in CFLs compared to LED luminaires due to the difference in the way the phosphor is coated/sandwiched. In order to understand the effect of heating on intensity variation and hence to decouple the effect from vibrations, a CFL (ecosmart) lamp was subjected to experiments without vibrations. Thus, the heating over many hours may partially account for the intensity variations, but not entirely. This effect especially does not account for increases in intensity. CFL (Ecosmart) performed the best of all three luminaires. LED was comparable to CFL (Ecosmart) and CFL (NUVUE) was the worst.
5.2 Recommendations

- Repeat the experiments with more lamps and develop a statistical distribution of data.
- Repeat the experiment with less or more than 24 hours.
- Repeat the experiments with the same lamp with periods of no vibration in between.
- Analyze data and come up with reasons and possible.
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VITA

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