Experimental Characterization of Arc Motion and Light Flicker Frequencies in HID lamps. Application to CDM-T Elite 50W/930 and 35W/930

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Abstract: In order to reduce the electric consumption for high intensity discharge lamps, the use of high frequencies electronic ballasts represents both a solution and many advantages such as the decrease in the congestion and low costs. However, high frequency operation is not regarded as perfectly reliable due to the appearance of acoustic resonances inside the arc tube, which can result in low frequency light flicker and even lamp destruction. Therefore a predictive model was established in order to give us at which frequencies light flicker can be expected. Moreover, we conducted an experimental study, which allows the electrical detection of frequency regions, in which the discharge arc behaves instable. Furthermore, an optical system is incorporated to record images of the discharge arc during stable and instable operating conditions. The results enable a considerably better understanding of the flicker phenomenon in HID lamps and facilitate the development of energy efficient drivers.

Keywords: Acoustic resonance, Fast Fourier Transform FFT, photodiode, Arc Motion, CMOS image sensors.

1. Introduction

Lighting is one among numerous applications in which the electric discharge is important. At first low pressure lamps dominated the market as the first artificial luminous sources, then the development of high intensity discharge lamp permitted the creation of light sources producing an important luminous flow. This flow permitted the lighting of wide public spaces. The difference is that the volume in high intensity discharge lamps presents an improvement in regard to that of low pressure lamps, in addition to the lamp life and a better control of its functioning, thus reducing electricity consumption [1-2].

These lamps prove to emit light at a high lumen output levels with a very high quality of colour. Low frequency drivers operate the HID lamps, operating these lamps at a high frequency high to 300 kHz achieve an efficency enhancement, but the alternative current generates a periodic heat source in a form of plasma discharge arc [3 - 5].

Pressure oscillations are implied by the fluctuating temperature field, a material flow is generated through an acoustic streaming phenomenen by the induced standing pressure waves, this happens when the driving current is at acoustic eigenfrequency of the arc tube. The buoyancy driving velocity field is then affected, as a consequence, arc motion or high intensity fluctuations are created. We have measured current, voltage, electric power for the determination of the acoustic resonance frequencies. The flickers at that step of work are not investigated a lot [6 - 9].

In our paper, a predictive model was established, translated into calculation program under the Matlab language through which we could determine the oscillations frequencies for the fundamental propagation modes. For a thorough understanding of the instabilities, accompanying experimental investigations have to be conducted. These investigations should be able to electrically and optically quantify the discharge arc at stable and instable operating conditions. Especially, changes during acoustic excitation of the arc tube content should be detected. The results of the experiments and simulations have to be discussed.

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2. Physical modelling of acoustic resonance

The shape of the discharge arc in the HID lamp depends on many factors: Arc tube geometry, electrode distance, absolute pressure inside the arc tube, type and amount of metal halides, mounting position, input power, etc. These factors influence the arc constriction, the arc length, the temperature distribution, the acoustic eigenmodes and their corresponding frequencies as well as many other physical fields. To increase the light quality and the conversion efficiency from electric power to visible light, the lamp can be operated at higher halogen pressures. However, this results in constricted arcs that are more susceptible to acoustic instabilities, [10-11].

The proposed physical model of acoustic resonance, allows to predict excitation conditions of acoustic resonance and the arc form. This model is obtained when considering the discharge in the lamp as a plasma in Local Thermodynamic equilibrium (LTE).[12] Under these conditions all the plasma's sizes are a temperature function often very complicated. A precise measurement carried out within the laboratory to obtain the geometrical profile of the plasma temperature is necessary for the determination of the acoustic resonance frequencies. We can completely model the behaviour of the discharge by using the conservation relations of the mass, momentum and energy, coupled with electric relations and those of the radiation. Considering the loss by friction due to the plasma viscosity insignificant, which means that we can omit the terms of amortization, which leads to the following equation, characterizing the propagation of the pressure waves in the plasma. [13]

$$\frac{\partial^2 p}{\partial t^2} - C_S^2 \Delta p = (\gamma - 1)\frac{\partial N}{\partial t} \quad (1)$$

$$N = P_{ele} - U_{ray} - W_{th} \quad (2)$$

$$C_S = \sqrt{\gamma.\frac{R_M.T}{M}} \quad (3)$$

The equation (1) is very complex and requires the knowledge of a great number of data and its solution is extremely difficult. However, if our reasoning is limited just to the prediction of frequencies where the acoustic resonances appear, we then can omit the term source which depends only on the plasma. So we will treat the propagation of pressure wave in a hot gas but not ionized. In this context certain terms of the model may be neglected and the equation is considerably simplified. After simplification, we gets:

$$\nabla^2 p = \frac{1}{C_S^2(T)}.\frac{\partial^2 p}{\partial t^2} \quad (4)$$

This simplified formulation, known as "Helmholtz equation" makes it possible to determine the acoustic resonance frequencies. If, initially we consider that the temperature and the speed of propagation of sound are constant, [14]. Under these conditions this equation can be analytically solved, in a cylinder of ray R and length L, by the variables separation method:

$$P(r,\varphi,z,t) = P_A J_n\left(\frac{W_r r}{C_s}\right)\cos(n\varphi)\cos(\frac{W_z Z}{C_s})e^{-j\omega t} \quad (5)$$

$$\omega_{nlm} = \sqrt{\left(\frac{a_{nm}C_s}{R}\right)^2 + \left(\frac{\pi l C_s}{L}\right)^2} \quad (6)$$

According to the equation (6), the acoustic resonance frequency depends then on the dimensions of the discharge tube (ray R and length L), and the celerity of the pressure propagation Cs which itself depends on the composition of gases and average temperature of the plasma.

This means that the resonance frequency may vary with the ageing of the lamp because of the change of gas compositions, and with the temperature which represents the total power injected into the discharge. Consequently, because of the manufacture tolerance, we can have light differences in acoustic resonance frequencies for lamps of the same type and manufacturer.

For the equation (5), terms (n,m,l) represent as well the spatial distribution of pressure in the discharge, by indicating $\omega_{nm} = \omega_r$ the transverse frequency of resonance according to (r,φ), by ωl = ωz the longitudinal frequency of resonance according z, and by ωn,m,l = ω the combined resonance frequency or global. The equation (5) enables us to distinguish the following terms:

$$P(r,\varphi,z,t) = \overset{Amplitude}{P_A} \overset{termeradial}{\left[J_n\left(\frac{W_r r}{C_s}\right) \right]} \overset{termeAzimuthal}{\left[\cos(n\varphi)\right]} \overset{termeLongitudinal}{\left[\cos(\frac{W_z Z}{C_s})\right]} \overset{Propagation}{\left[e^{-j\omega t}\right]} \quad (7)$$

2. Experimental setup

The experimental setup was mainly used to determine the acoustic eigenfrequencies of the arc tube of the HID lamp. Additionally, the setup served to investigate the hysteresis effect. Optical measurement devices were implemented in this setup to detect the emitted light of the discharge arc during stable and unstable operation. Figure.1. schematically depicts the experimental setup that consists of the HID lamp itself, the equipment necessary to operate the lamp and different measurement devices. Furthermore, the manufacturer and the product name are presented. The HID lamp, a Philips MASTER Colour CDM-T Elite 35W/930, was operated at a square-wave voltage with a carrier frequency f_c= 400 Hz. The square wave signal was provided by an Agilent 33220, [15]. A function generator with arise and fall time of less than 13 ns and an over shoot of less than 2%. No instabilities of the discharge arc occurred at f_c because the driving frequency was considerably smaller than the lowest acoustic eigenfrequency at approximately 42 kHz. The second function generator, a Wavetek Mode 29A, produced a sinusoidal voltage with a resolution of 0.1 mHz that was used to excite discharge arc flicker. For this reason, the frequency of this signal is also called excitation Frequency f_{ex}, [16]. It was tuned to different frequencies in a certain high frequency range. The power amplifier, a MTMedTech FM 1295, regulated the amplitude of the voltage V(t) and the electric current I(t) so that the HID lamp was operated at its nominal power. The modulation depth α describes the ratio of the sinusoidal to the square wave voltage amplitude. The power can be derived from P(t) = V2(t)/Rplasma with the electric resistance of the plasma Rplasma. The power analyser, a Yokogawa PZ 4000 , measured the following data : The electric current, the electric potential drop between the electrodes and the electric power.[17]

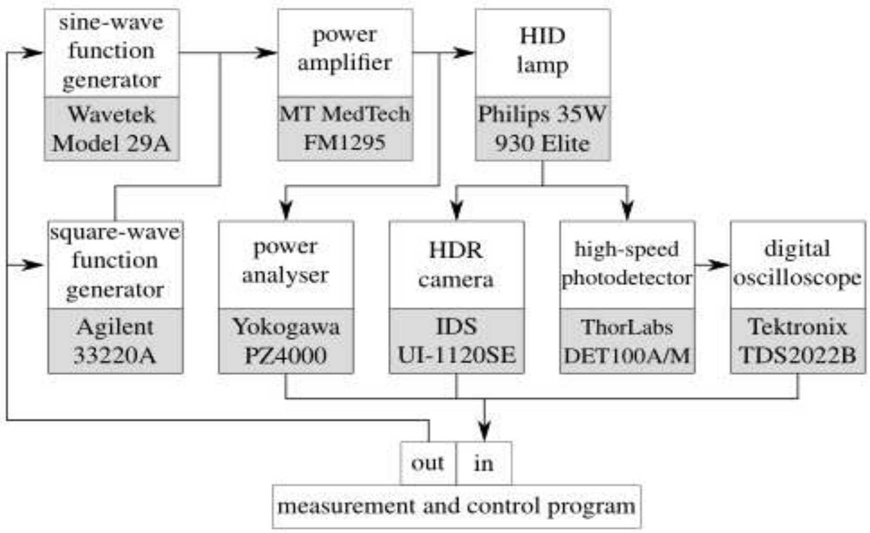

Figure 1. Experimental setup to characterise discharge arc flicker in HID lamps.

The high dynamic range (HDR) camera, a IDSUI-1120SE, enables direct observation of the

discharge arc because it can resolve the high brightness differences between the arc and its surrounding.[18] The CMOS chip of the camera is sensitive in the wave length range of 400 nm to 900 nm with the highest sensitivity at 710 nm, has a resolution of 768×576 pixels and a high dynamic range of 120 dB.[19] The maximal refresh rate of the camera is 50 Hz. When the discharge arc flicker was investigated experimentally, both the camera and the high speed silicon photodetector, a DET100A/M from ThorLabs, were used. The photodiode with a rise time of 43ns converts the brightness fluctuations into an electric current. The spectral sensitivity is 400 nm to 1100 nm with a peak wave length at 970 nm . The photodiode was placed in a distance of 0.2 m from the HID lamp to receive enough illumination and simultaneously to prevent saturation. The digital oscilloscope, a Tektronix TDS2022B, records the time dependent signal and converts it into the frequency domain by fast Fourier transform (FFT).[20]
A computer transmitted the values of the modulation depth and the excitation frequency to the function generators and records the camera and photodiode signals as well as the electric current, electric potential drop and electric power. To control the experimental setup, program code created with MATLAB was used. To determine the acoustic eigenfrequencies that lead to a flickering discharge arc, the lamp was initially operated at a modulation depth of 0% for at least ten minutes. The lamp reached a stationary state at this stable condition, which means that the temperature inside the arc tube, the voltage drop between the electrodes, their radiated light, do not change anymore. The constant electric potential drop between the electrodes without acoustic excitation is defined as the reference voltage (V_{ref}). In case of the exemplary measurement in Figure 2,V_{ref} is 90 V (f_{ex}= 40.0 kHz, α = 0%).

The electric potential is proportional to the arc length because the passage of current through the plasma acts as an ohmic resistance. Therefore, arc flicker can directly be observed by measurement of the voltage drop, [21]. After the stationary state was reached, f_{ex} was set to a constant value near an acoustic eigenfrequency of the lamp and α was step wise increased every 10 s to excite acoustic waves. Meanwhile, the potential drop was measured every 0.5 s, and the power was regulated to keep it at its nominal value. When the voltage fluctuated more than V_{fluc}= 1.5 V or when the voltage exceeded Vlim= V_{ref}+5.0 V, the measurement was aborted to prevent lamp failure caused by exceedingly high arc tube temperature or by temperature oscillations of the arc tube. Immediately afterwards, α was set back to 0% and f_{ex} was increased to the next frequency step.

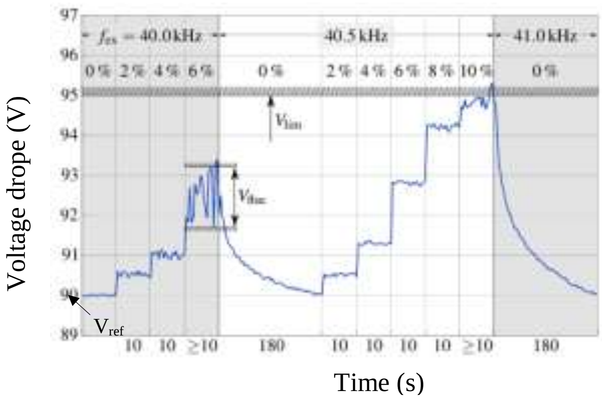

Figure 2. Exemplary behaviour of the voltage drop during determination of acoustic eigenfrequencies.

Figure 2 displays both cases of measurement abortion. A voltage fluctuation of more than Vfluc occurs at f_{ex}=40.0 kHz and α=6%, and the voltage limit V_{lim} is exceeded at f_{ex}= 40.5 kHz and α=10%. For the 35 W lamp, the excitation frequency was generally increased from 35 kHz to 50 kHz in 500 Hz steps to excite the first instability at around 42kHz. The modulation depth was increased from 0% to 12% in 2% steps.

4. Simulation Results

Table 1. Lamps characteristics

Standard lamp SHP 400W	standard lamp VMHP 400W with 70mg
R= 3,75 e-3 m.	R= 9,5 e-3 m
L= 10,7 e-2 m.	L= 8,2 e-2 m
Cs= 470,7 m/s2	Cs= 491,71 m/s2

A. SHP lamp

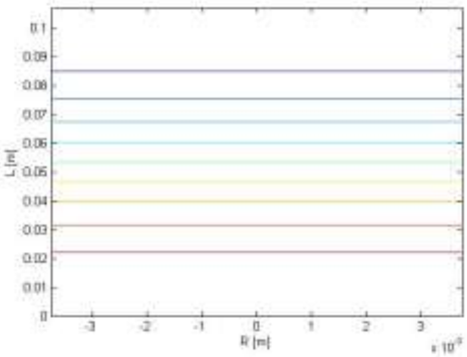

Figure 3. Longitudinal fundamental mode (0,0,1).

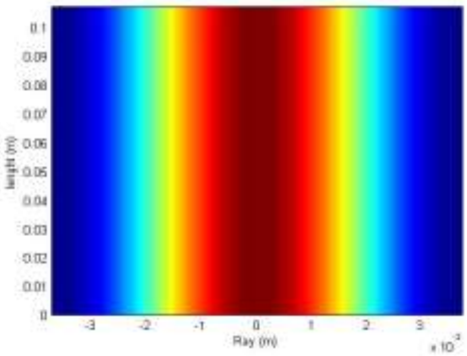

Figure 4. Radial fundamental mode (0,1,0)

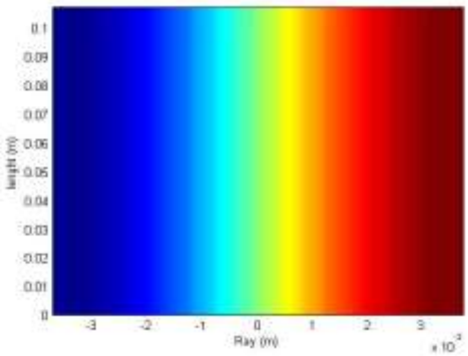

Figure 5. Azimuth fundamental mode (1,0,0).

B. VMHP results

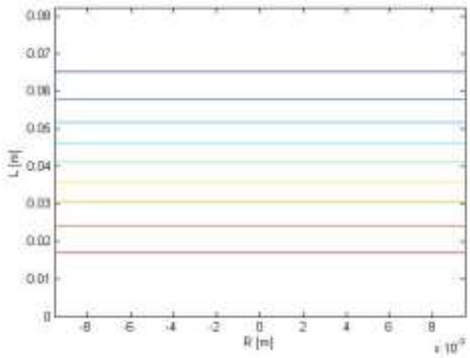

Figure 6. Longitudinal fundamental mode (0,0,1)

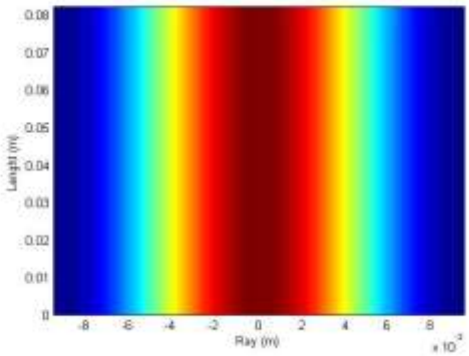

Figure 7. Radial fundamental mode (0,1,0)

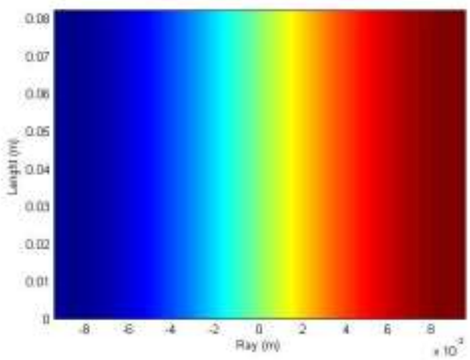

Figure 8. Azimuth fundamental mode (1,0,0)

For all graphs:
- high pressure
- Null pressure
- Low pressure

Table 2. Frequencies of the acoustic resonances

Mode / Lamp Type	(0,0,1)	(0,1,0)	(1,0,0)
SHP 400 W	2.1995 kHz	76.5464 kHz	36.7819 kHz
VMHP 400W	2.9982 kHz	31.5644 kHz	15.1672 kHz

According to the distribution of pressure in the arc and we note to the theory that the discharge endeavours to move through zones where the pressure is low. The arc takes the way which corresponds to the least losses.

For longitudinal mode Z axial (0,0,1) we can see clearly that the pressure begins to take important values starting from 0.045m for the HPS lamp whereas for the HPMV lamp it starts from 0.035m. For radial longitudinal mode R axial (0,1,0), the higher pressures lies between -0,8.10-3 m and 0,8.10-3m for HPS lamps type and between -2.10-3m and 2.10-3 m for HPMV lamps type. The φ axial, azimuth mode (1,0,0) the pressure starts to get important values from 2,5.10-3m for HPS lamp while for the HPMV this value is equal to 5,8.10-3m.

Concerning the two modes longitudinal Z-axial (0,0,1) and R-radial (0,1,0), we remark well that the probability to get an acoustic resonance effect is important in the case of HPMV lamps type than that of HPS ones, then it is reversed for the φ axial azimuth mode (1,0,0). In experiments this effect is translated as follow, the Acoustic resonance in longitudinal mode arises by a curved arc at the level of one of the discharge ends. In radial mode, the arc seems to segment successively to diffuse zones then narrow. Finally, the azimuth mode is an oscillation of the arc from one end to another.

5. Experimental results

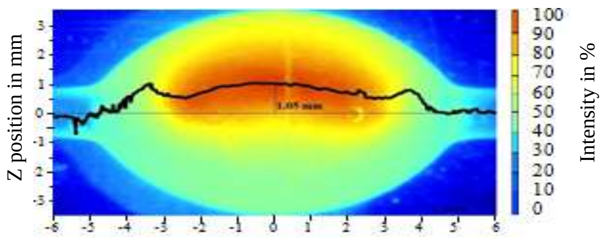

Figure 9. Experimental determination of arc deflection at unstable operating conditions.

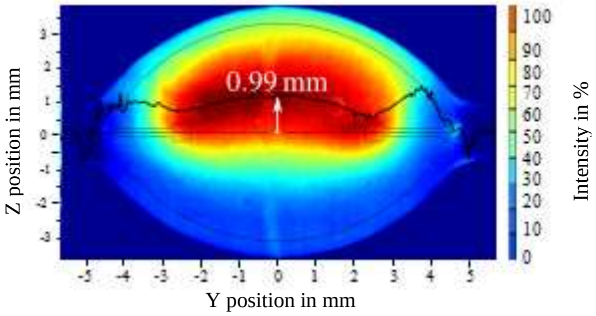

Figure 10. Experimental determination of arc deflection at stable operating conditions.

Exemplary light intensity measurement of a horizontally operated HID lamp. The black line indicates the mean position of all light intensity values that are larger than 95% times the highest light intensity as a function of the y coordinate. The main results of the optical measurements are presented in Figure.10 The fluid flow bends the discharge arc upwards so that an arc deflection of 0.99mm at y=0mm occurs in the exemplary image shown on the figure. Additionally, this image illustrates the translucency of the tube wall: The image is not sharp, but blurred. As the arc tube consists of two welded half-shells, the weld seam refracts the light. Consequently, a lower intensity in the z-direction is measured that appears as a vertical stripe at y≈0mm.

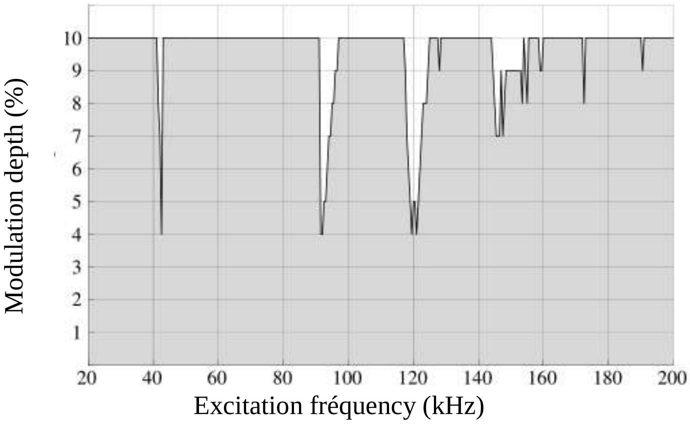

Figure 11. Experimental detection of acoustic instabilities over a wide frequency range.

Figure 11 presents an overview of a wide frequency range of 20kHz to 200kHz, in which arc flicker in the investigated HID lamp occurs. The modulation depth in this experiment was varied from 0% to 10% in 1% steps. In the grey coloured area, no arc flicker was detected and, hence, the lamp could stably be operated. The maximum modulation depth was not reached at some excitation frequencies because the voltage drop exceeds one or even both termination criteria. These consist of the voltage fluctuation Vfluc≥1.5V measured at one operating point (specific excitation frequency fex and modulation depth α) and of a voltage limit of Vlim≥Vref+5.0V that exceeds the reference voltage measured at a modulation depth of 0%. Thus, the termination prevents operation at higher modulation depths at this excitation frequency to prevent lamp failures that are caused by pressure fluctuations or exceedingly high pressures inside the arc tube. With regard to the amplitude (modulation depth), the experimental results show an increasing loss with an increasing excitation frequency because the modulation depth necessary to excite flicker increases. We notice that up to 120 kHz a modulation depth of 4% is sufficient to excite flicker, but a higher modulation depth is necessary at frequencies beyond 120 kHz.

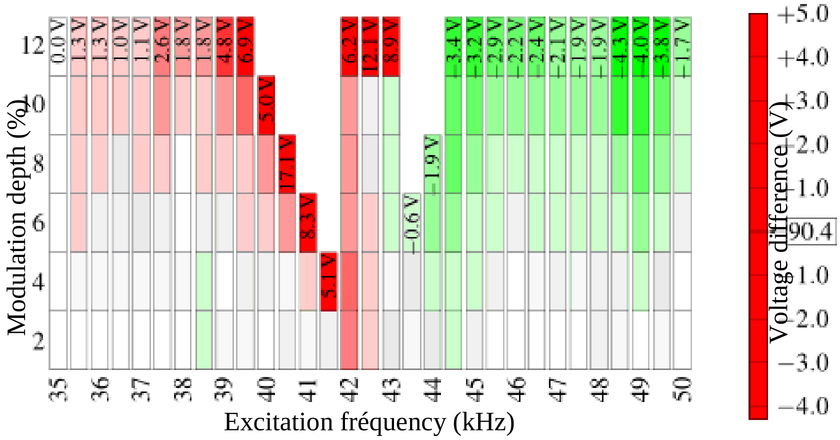

Figure 12. Measurement of the AR at the lowest excitation frequency at which arc flicker occurred.

For a more detailed analysis, the acoustic resonance at the lowest frequency, that shows arc flicker, was chosen in order to reduce the probability of measuring a superposition of acoustic eigenmodes. The frequency region of these detailed measurements ranges from 35 kHz to 50 kHz in 500 Hz steps, and the modulation depth was increased from 0% to 12% in 2% steps. Figure.10 shows the detection of the acoustic resonance of a certain lamp. In addition to the threshold value of the modulation depth for each excitation frequency, the corresponding result of the measured voltage drop for each operating point is shown. In the scale, the reference voltage Vref=90.4V is pointed out. Measured voltages that are higher than Vref are marked in red and operating points with a lower voltage are coloured green. The scale of the excess voltage is limited to 5.0V, which corresponds to Vlim. Additionally, the measured voltage at the last operating point for each excitation frequency is presented. A higher voltage is the result of an increasing arc length so that the arc deflection increases as well. In contrast to that, the green colour indicates operating points with a decreasing arc deflection (arc straightening). The intensity of the colour represents the strength of the voltage difference to Vref and, consequently, the strength of the deflection change. This was observed by eye and proved by measurements with the camera.

In general, two different discharge arc behaviours can be observed in Figure.12 that are caused by different mechanisms. Up to fex=42.5 kHz, the voltage increases when increasing the modulation depth. At higher excitation frequencies, the voltage decreases. The strength of the voltage difference to Vref rises with increasing modulation depth because the share of the excitation part in relation to the stable part grows. The two local minima in the modulation depth are related to two different modes. The results of lamp highlight that the first minimum occurs at fex=41.5 kHz and the second minimum at fex=43.5 kHz. The voltage exceeds Vlim at fex= 41.5 kHz, whereas a fluctuating voltage Vfluc of a slightly straightened arc was detected at fex= 43.5 kHz. At the three measured frequencies between these two minima, the experiment terminated at α=12%. The measured voltage at α = 2% and fex= 42.0 kHz is conspicuous because it is considerably higher than voltages at the same modulation depth at other excitation frequencies.

The measurements serve to identify the mean values as well as the standard deviations of the reach able modulation depths and the frequencies, at which the lowest modulation depth is attained. Qualitatively, the results coincide with those presented before hand; especially the results shown in Figure.12 Up to excitation frequencies, at which the lowest modulation depth occurs, the voltage increases with modulation depth.

At higher excitation frequencies, arc straightening (decreasing voltage with increasing modulation depth), was detected. Quantitatively, the results differ from lamp to lamp of the same kind because geometry and gas composition tolerances occur in the manufacturing process.

6. Conclusion

The developed and verified simulation model facilitates the study of acoustic resonances that lead to light flicker in high intensity discharge lamps. The findings help to understand the underlying physical processes considerably better, which is crucial for an improvement of the lamp and driver design. The validated model enables development of new lamp systems that operate at stable conditions, possess an improved energy efficiency, are less bulky, are characterised by lower costs and have a reduced amount of mercury or even avoid this heavy metal. The simulation of instable discharge arc behaviour allows to design new electronic drivers that operate in the high frequency range and, therefore, have a significantly higher energy efficiency compared to state of the art lamps. Moreover, the model is helpful to identify acoustic eigenmodes that induce a fluid flow that causes arc straightening, which is equivalent to a stabilisation of the discharge arc and leads to a further increased energy efficiency. Forfurther investigation of the acoustically induced streaming field in high intensity discharge lamps, some advancements are recommended. First, it would be beneficial to compare our results to additional experimental data. Especially, the velocity field inside the arc tube is of interest because it induces the arc flicker. Instead of an indirect detection of the fluid flow by voltage and light intensity measurements or by theoretical considerations, experimental results would be useful in benchmarking the simulation. The laser Doppler anemometry enables such measurements, but requires special lamp types with a transparent arc tube material and, therefore, necessitates a simulation model with a different geometry and adjusted transport coefficients.

7. Acknowledgment

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Nomenclature:

P: Variation of the pressure around the average value P_0.

N(w): Electric power injected volume unit.

P_{ele}: Electric power injected in the discharge.

U_{ray}(W) : Losses radiation by volume unit.

W_{th}(W) : Heat dissipation by volume unit, due to thermal conduction.

γ : Constant defined as the ratio of the specific heats to the pressure and constant volume (respectively Cs and Cv).

R_M: Gas molar constant.

$R_M = 8{,}3144 \ (j^{-1}.mol^{-1}.K^{-1})$.

M : Mass molar $(mol.g^{-1})$.

T (K): Discharge temperature.

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