Life prediction of LED-based recess downlight cooled by synthetic jet

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Abstract

This paper details the adaptation and implementation of a proposed hierarchical model to the reliability assessment of LED-based luminaires. An Edison base – 6 in., compatible can, downlight – LED replacement bulb, cooled by active synthetic jets, is used as the test vehicle. Based on the identified degradation mechanisms and the experimentally obtained degradation rate of the cooling device, the reduction in the heat sink enhancement factor, and thus the increase in the LED junction temperature, is determined as a function of time. The degradation mechanisms of the dual-function power electronics – providing constant power to the LEDs and to the drivers of a series of synthetic jets – are also analyzed and serve as the basis for a hybrid model which combines these two effects on the luminaire lifetime. The lifetime of a prototypical luminaire is predicted from LED lifetime data using the degradation analyses of the synthetic jet and power electronics.

1. Introduction

Various types of LED-based luminaire released in the market have been attracting considerable interest due to advantages such as compact size, high color quality, high luminaire efficacy, and long lifetime compared to conventional light sources (Table 1) [1]. Although LEDs are attractive for lighting applications due to the aforementioned advantages, the extreme sensitivity of light output and useful lifetime to the LED junction temperature remains a unique technical challenge. To overcome this challenge, innovative passive and active cooling solutions have been developed continuously, and thus appropriate methodologies to assess the reliability of LED-based luminaires are required.

Typical LED-based luminaires consist of LED light engine, cooling device, optical component, and power electronics. Each component has unique degradation mechanisms. In order to assess the reliability of the luminaire, a hierarchical reliability model was proposed by the authors [2]. In the paper, the concept of the hierarchical model was described and its implementation was illustrated by assuming some possible degradation mechanisms.

This paper is an extension of our previous research [2], and details a procedure to adopt and implement the hierarchical model for an actual LED-based luminaire. Section 2 describes the LED-based luminaire cooled by a synthetic jet and presents a refined hierarchical model that is specifically aimed for the luminaire. In Section 3, the synthetic jet is analyzed in detail and the junction temperature change due to the degradation of the cooling device is evaluated. The effect of power electronics degradation on the luminaire is provided in Section 4. Finally, in Section 5, the lifetime of the luminaire is predicted from the LED lifetime using the results of the analyses of the previous sections.

2. Luminaire and hierarchical lifetime prediction model

2.1. Description of luminaire

The high brightness LED-based luminaire analyzed in the paper is shown in Fig. 1a [3]. The luminaire is an Edison base, 6 in. compatible can downlight, LED replacement bulb producing 1500 face lumens at 75 lm/W, CRI > 80, CCT = 2700–3200 K [3]. In order to deliver the proper beam uniformity and angle of light while satisfying the size constraints, polycarbonate lens are employed. They provide an overlapping beam with approximately 50° beam angle control.

The luminaire is actively cooled by synthetic jets. Synthetic jets are zero net mass flow devices that comprise a cavity or volume of air enclosed by a flexible structure and a small orifice through which air is forced [4,5]. The structure is induced to deform periodically in a bending mode causing corresponding suction and expulsion of air through the orifice. A synthetic jet employed in the luminaire is shown in Fig. 1b. It comprises two thin piezoelectric actuators separated by a compliant ring.
piezoelectric actuator comprises a metallic substrate bonded to a piezoelectric material.

As the power electronics drives the LED light engine as well as synthetic jets, a fly-back converter topology was chosen to provide galvanic isolation between the input ac voltage of 120-V rms at 60 Hz and the output voltages. The fly-back transformer converts an input voltage (with peak value \( V_p \)) to dc voltages for the LEDs and synthetic jets [3].

### 2.2. Hierarchical life prediction model

The concept of a hierarchical model was proposed in Ref. [2]. A model refined to be specifically aimed for the luminaire of Fig. 1a is presented in Fig. 2. The model is articulated on four levels: LED chip/package, optical components in the fixture, synthetic jets with a heat sink, and power electronics. Fig. 2 also shows all the sub-models and the associated loading conditions at each level.

The lifetime of the luminaire is determined by the lumen maintenance of LED and the reduction of the fixture efficiency, which can be expressed as [2]:

\[
t_{\text{life}} = F(g_{\text{LED}}(t), F_{\text{fixture}}(t)) \tag{1}
\]

where \( t_{\text{life}} \) = luminaire lifetime at lumen maintenance of 70%, \( g_{\text{LED}} \) = lumen maintenance of LED, and \( F_{\text{fixture}} \) = fixture efficiency.

The lumen maintenance of LED is the most critical sub-model. Using an empirical exponential form [6,7], the light output of LEDs, \( L_{LED} \), can be expressed mathematically as:

\[
L_{LED} = L_0 g_{\text{LED}}(t) = L_0 e^{-\frac{t}{t_{\text{life}}}} \tag{2}
\]

where \( t \) is the light output degradation rate that is a function of the junction temperature \( (T_j) \) as well as the forward current \( (I_f) \) [8–10]. \( t \) is the operation time measured in hours, and \( L_0 \) is the initial light output in lumen.

The cooling performance of synthetic jets is expressed with an enhancement factor \( (EF) \) which is defined as the ratio of heat removed with an active cooling device \( (Q_{\text{active}}) \) to the heat removed through passive means only, largely through natural convection \( (Q_{\text{nc}}) \), at the same temperature, i.e., \( EF = \frac{Q_{\text{active}}}{Q_{\text{nc}}} \). Considering the fact that the junction temperature increases as the ambient temperature and forward current increase, the dependence of the junction temperature on the aforementioned terms can be expressed as [2]:

\[
T_j = T_0 + \left( R_{\text{cond}} \cdot I_f \cdot EF \right) \tag{3}
\]

where \( T_0 \) = ambient temperature; \( R_{\text{cond}} \) = internal conduction resistance of LED.

The power electronics drives the LED light engine as well as the synthetic jets. The degradation of power electronics is mainly caused by capacitance reduction of electrolytic capacitors. The reduced capacitance increases the ripple voltage, and thus the applied current to LED is reduced [11]. The decreased current affects the light output and junction temperature. As mentioned above, the decay constant is a function of forward current; as a result the decay constant decreases with the decreasing current.

The remaining sub-models of the proposed hierarchical model are physics-of-failure (PoF) models to describe the degradation mechanisms of the synthetic jet performance. The PoF models of the synthetic jet degradation can be separated into depolarization of the piezoceramic disk and aging of the compliant ring. The degradation mechanisms change the displacement amplitude response of the synthetic jet, thereby reducing the \( EF \) at any given time.

### 3. Reliability analysis of synthetic jet

The degradation of synthetic jet performance (i.e., the reduction in displacement amplitude) increases the junction temperature of the luminaire, which is a dominant factor for the lifetime of the luminaire. After developing a model that can predict displacement amplitude response, the time-dependent performance of the synthetic jet can be predicted by aging characteristics of each component in the synthetic jet. The performance change is then converted into the junction temperature change using the relationships between the amplitude of the synthetic jet and junction temperature.

#### 3.1. Performance characterization

The performance of the synthetic jet was tested by applying a harmonic voltage input at various frequencies. The center out-of-plane displacement amplitudes of the disk were measured by a laser doppler vibrometer [CLV-1000, Polytech].

The junction temperature is directly related to the performance of the synthetic jet and the heat sink. The enhancement factor \( (EF) \) is proportional to the amount of air-flow rate, which is a function of the amplitude of the jet and the excitation frequency.

Assuming that the deflection of the disk can be modeled as a part of a perfect sphere, the air flow rate can be approximated as (Fig. 3):
AFR = \frac{4\pi}{3} \left( (R - a)^3 - R^3 \right) \times f_{\text{jet}}

(4)

where AFR = air flow rate; \( f_{\text{jet}} \) = operating frequency of synthetic jet; \( a \) = amplitude of synthetic jet; and \( b \) = radius of nickel coated substrate. Geometrical considerations require that, the radius of the sphere, \( R \), be expressed as \( R = \frac{a^3 + b^3}{a^2} \).

A relationship between the \( \text{EF} \) and the air-flow rate is depicted in Fig. 4a, which was obtained by changing the amplitude of the disk (or by changing the amplitude of the excitation voltage) at a fixed excitation frequency. In order to determine the junction temperature for a given \( \text{EF} \), an empirical relationship should be obtained for each synthetic jet and heat sink design. Fig. 4b shows such a relationship, obtained from synthetic jets incorporated with a radial heat sink.

The enhancement factor decreases as the synthetic jet ages. The aging is caused by two degradation mechanisms: depolarization of the piezoceramic and change in the elastic modulus and damping ratio of the compliant ring. This can be expressed as:

\[
\text{EF} = \text{EF}(P_{\text{jet}}); \quad P_{\text{jet}} = P_{\text{jet}}(T_a, D_{\text{pzt}}, E_{\text{td}}, \zeta_{\text{td}}, P_{\text{ps}})
\]

(5)

where \( P_{\text{jet}} \) = performance of jet; \( D_{\text{pzt}} \) = depolarization effect of piezoceramic; \( E_{\text{td}} \) = elastic modulus change of compliant ring; \( \zeta_{\text{td}} \) = damping ratio change of compliant ring; and \( P_{\text{ps}} \) = performance of synthetic jet driving circuit.

3.2. Hybrid modeling

The amplitude reduction can be predicted using numerical modeling if the degradation rates of the piezoelectric disk and the compliant ring are known. A hybrid experimental/numerical model is developed to predict the amplitude reduction as a function of time by adopting the property degradation characteristic of each material used in the synthetic jet.

A commercial FEM package (ANSYS 12.1) was used to build an FEM model for harmonic analysis using quarter symmetry (Fig. 5a). In order to incorporate material damping, Rayleigh damping was used [12], which can be expressed as:
f_{mr} = \frac{a}{2x_R} + bx_R^2 \quad (6)

where $f_{mr}$ is the $r$th modal damping ratio, $x_R$ is the resonant frequency in rad/s, $a$ is the mass damping multiplier, and $b$ is the stiffness damping multiplier. Since $a$ is zero for the current case of viscous damping \[12\], Eq. (6) can be rewritten as:

$\beta = \frac{2f_{mr}}{\omega_k} \quad (7)$

The damping ratio of each material in the synthetic jet was converted to $\beta$ by using Eq. (7). Fig. 5b shows the comparison between simulation and experimental result at vacuum condition. The simulation result is in good agreement with experimental results.

The ambient pressure at the operating condition is 1 atm and thus the effect of the air damping known as “squeeze film damping” \[13\] must be considered in the modeling. Squeeze film damping occurs when two surfaces separated by a thin viscous fluid film move symmetrically. This effect is illustrated in Fig. 6a, where the amplitude response of the synthetic jet at 1 atm and the vacuum are compared. As expected, the resonant frequency and the amplitudes were altered significantly with damping: the resonant frequency decreased and the amplitude at the resonant frequency also decreased.

The data of Fig. 6a was normalized and plotted again in Fig. 6b to distinguish the characteristics of amplitude distributions more clearly. The frequency and the amplitude were normalized by the resonant frequency of each case and the amplitude at the resonant frequency, respectively. It can be seen from Fig. 6b that the amplitudes at frequencies other than the resonant frequency tend to decrease more slowly with the air damping, especially at the frequencies higher than the resonant frequency ($f > f_k$). An advanced CFD model can be used to handle the squeeze film damping effect. In this study, a hybrid numerical/experimental scheme was developed since the reliability model only concerned the final amplitude.

The rationale for the hybrid approach can be explained by comparing the numerical prediction of synthetic jet with the experimental data. The goal of the approach is to force the numerical prediction to match the experimental data by effectively adjusting the original properties to account for the effect of squeeze film damping.

The jet is essentially a second order system subjected to a sinusoidal input. The resonant frequency of the second order system, $\omega_k$, is expressed as \[14\]:

$\omega_k = \omega_0 \sqrt{1 - 2\zeta^2} = \sqrt{\frac{k}{m} - \frac{c^2}{2m^2}} \quad (8)$

where $m$ is the mass, $c$ is the damping coefficient, $k$ is the stiffness, $\zeta$ is the damping ratio ($\zeta = \frac{c}{\sqrt{k,m}}$), and $\omega_0$ is the natural frequency ($\omega_0 = \sqrt{\frac{k}{m}}$). For a given mass, the resonant frequency can be changed by adjusting the stiffness or the damping coefficient.

The amplitude of the second order system subjected to a harmonic excitation is expressed as \[14\]:

$A = \frac{F}{\sqrt{1 - 4\zeta^2}} \quad (9)$

where $F$ is the force magnitude.
where $X$ is the amplitude at each frequency, $F_0$ and $\omega$ are the excitation force and frequency, respectively. Eq.(9) implies that the most practical way of adjusting the amplitude is to manipulate the force.

Using Eqs.(8) and (9), the amplitude normalized by the value at the resonant frequency can be expressed as:

$$X = \frac{F_0}{k} \frac{1}{\sqrt{(1 - \frac{\omega^2 m}{\omega^2 k})^2 + (\frac{\omega c}{\omega k})^2}}$$

(9)

where $X$ is the amplitude at each frequency, $F_0$ and $\omega$ are the excitation force and frequency, respectively. Eq. (9) implies that the most practical way of adjusting the amplitude is to manipulate the force.

Using Eqs. (8) and (9), the amplitude normalized by the value at the resonant frequency can be expressed as:

$$\frac{X}{X_R} = \frac{(\frac{1}{\sqrt{(1 - \frac{\omega^2 m}{\omega^2 k})^2 + (\frac{\omega c}{\omega k})^2}})}{(\sqrt{(1 - \frac{\omega^2 m}{\omega^2 k})^2 + (\frac{\omega c}{\omega k})^2})}$$

(10)

For a given mass, the normalized amplitude can also be changed by adjusting the stiffness or the damping coefficient.

A sequential optimization procedure was developed for the hybrid approach. The flowchart is shown in Fig. 7 and the detailed description of each step is provided below.

- **Step 1: Profile of normalized amplitude**

Since the elastic and damping properties of the piezoceramic disk/substrate assembly do not change with time, the effective properties and the stiffness damping multiplier of the assembly are used to modify the system stiffness and the damping. The effective properties of the piezoceramic disk/substrate assembly can be expressed as:

$$E_{\text{eff}} = \frac{E_{\text{sub}} V_{\text{sub}} + E_{\text{PZT}} V_{\text{PZT}}}{V_{\text{sub}} + V_{\text{PZT}}}$$

$$\beta_{\text{eff}} = \frac{\beta_{\text{sub}} V_{\text{sub}} + \beta_{\text{PZT}} V_{\text{PZT}}}{V_{\text{sub}} + V_{\text{PZT}}}$$

(11)

where $E$, $\beta$ and $V$ represent the modulus, the stiffness damping multiplier and the volume, respectively. The subscripts of “sub” and “PZT” denote the substrate and piezoelectric disk, respectively.

The objective of this step is to adjust the amplitude response. The amplitude data normalized by the maximum amplitude was used to determine an effective $E-\beta$ combination by using an optimization routine (Eq.(9)). The objective function ($R_1$) can be expressed as:

$$R_1 = \frac{1}{n} \sum_{i=1}^{n} |\tilde{A}_{\text{exp}}^i - \tilde{A}_{\text{sim}}^i|$$

(12)

where $\tilde{A}_{\text{exp}}$ and $\tilde{A}_{\text{sim}}$ are the amplitudes of experimental and simulation data normalized by each maximum, respectively; and $n$ is the number of data points. The optimization routine adjusts the $E-\beta$ combination until the objective function has the minimum value. Fig. 8a shows the results obtained using the effective $E-\beta$ set at an input voltage of 30 V.

- **Step 2: Absolute amplitude**

The absolute amplitude level can be adjusted by changing the input voltage (Eq. (8)). The objective function ($R_2$) for the optimized $V$ quantifies the degree of coincidence between the experimental and the simulated data. The metric can be expressed as:

$$R_2 = |\bar{A}_{\text{exp}} - \bar{A}_{\text{sim}}|$$

(13)
where $A_{\text{exp}}$ and $A_{\text{sim}}$ is the average amplitude of all the experimental and the numerical data points, respectively.

The optimum combination of the effective properties and the input voltage is computed and the result obtained is compared with the experimental data in Fig. 8b. The result corroborates the effectiveness of the hybrid approach.

3.3. Depolarization of piezoelectric disk

The depolarization of the piezoelectric disk is attributed to the applied voltage, the mechanical stress, and the ambient temperature. If significant, it reduces piezo-coupling and thus reduces the displacement amplitudes of the jets. In order to characterize the depolarization effect, three groups of synthetic jets have been tested for 3000 h at three different temperature conditions (60, 90 and 120 °C). The planer coupling coefficient which indicates the amount of polarization property has been measured during operation.

Fig. 9 shows the experimental results. The coupling coefficient decreased initially but stabilized at 0.9, 0.86 and 0.81 for 60, 90 and 120 °C, respectively. The results confirm that the effect of depolarization on the piezoceramic disk is not significant and thus it will not be considered when the performance of the synthetic jet is to be evaluated in the PoF model.

3.4. Aging of compliant ring

For most polymers in oxygen-containing environments, oxidation is the dominant factor in aging [15]. The ductile polymer material becomes brittle due to the chemical reaction; the material modulus increases and the damping ratio decreases. In order to predict the material property change of polymer as a function of time and temperature, the Arrhenius relation, which is well known in chemical kinetics, can ascertain thermo-oxidative aging of polymers.

3.5. Time/temperature superposition method

The principle of time/temperature superposition was adopted to characterize the aging of the compliant ring. The time/temperature superposition is a well-known procedure, which can be applied to verify the temperature dependence of the rheological behavior of a polymer or to expand time or frequency regime for a polymer at a test temperature. This is accomplished by shifting the data along the time axis in a log scale. The shift factors $a_{T}$ are chosen empirically, to give the best superposition of the data. The shift factors $a_{T}$ are related to the Arrhenius activation energy, $E_{a}$, by the following expression [15]:

$$a_{T} = \exp \left( \frac{E_{a}}{R} \left( \frac{1}{T_{\text{ref}}} \frac{1}{T} \right) \right)$$  \hspace{1cm} (14)

where $a_{T}$ is the shift factor, $E_{a}$ is the activation energy, $R$ is the Boltzmann constant, $T_{\text{ref}}$ is the reference temperature, and $T$ is the testing temperature.

Eq. (14) can be rewritten as:

$$\ln(a_{T}) = \frac{E_{a}}{R} \left( \frac{1}{T_{\text{ref}}} - \frac{1}{T} \right)$$  \hspace{1cm} (15)

By plotting three shift factors using Eq. (15), the activation energy is obtained from the slope of the linear relationship.

3.6. Accelerated test for compliant ring

In order to characterize the aging behavior of the compliant ring, aging test has been conducted. Three different aging temperatures (230, 250 and 275 °C) have been selected to accelerate the aging rate. Ten specimens have been exposed to each temperature. DMA tensile tests were conducted to measure the storage modulus and the loss tangent (tan δ) at 175 Hz at various time intervals.

Fig. 10 shows the storage modulus and the loss tangent, changes over time at the three different aging temperatures. Each data point represents the average value of 10 specimens. The principle of time/temperature superposition was implemented with the reference temperature of 275 °C. All other curves were shifted to the curve at 275 °C to determine the shift factors.
The shift factors for the storage modulus and loss tangent were plotted in Fig. 11 (Eq. (15)). The slopes of linear lines represent the activation energies ($E_a$): the activation energies of the storage modulus and the loss tangent are 126 kcal and 128 kcal, respectively.

The data shifted by the shift factors are shown in Fig. 12. The results clearly indicate that the time/temperature superposition is valid for the data. The master curves for the storage modulus and the loss tangent can be expressed by the following exponential functions:

$$E(t; T) = A \exp \left( \frac{a_T(T)}{B} t + E_0 \right)$$  \hspace{1cm} (16)

$$\tan \delta(t; T) = C \exp \left( \frac{a_T(T)}{D} t + \tan \delta_0 \right)$$  \hspace{1cm} (17)

where $E(t; T)$ and $\tan \delta(t; T)$ are the time-dependent modulus and the loss tangent at a given temperature $T$. Three unknown constants ($A, B$ and $E_0$) for the storage modulus and ($C, D$ and $\tan \delta_0$) for the loss tangent can be determined by a non-linear regression analysis: the constants for Eqs. (16) and (17) are summarized in Table 2. The function described by Eqs. (16) and (17) are also shown in Fig. 12a and b, respectively.

The actual operating temperature of the synthetic jet is 55°C [3]. The shift factor for 55°C was obtained from Eq. (14): $8.63 \times 10^{-9}$ and $6.55 \times 10^{-9}$ for the storage modulus and the loss tangent, respectively. The change in storage modulus and loss tangent was subsequently predicted by Eqs. (16) and (17) and the results are shown in Fig. 13a and b. The storage modulus is predicted to be 3.8 MPa at 50,000 h while the loss tangent does not show any noticeable change.

3.7. Prediction of junction temperature vs. time

The amplitude change of the synthetic jet is shown in Fig. 14 (Eq. (4)), from which the enhancement factor ($EF$) is determined using the empirical relationship between $EF$ vs. air flow rate (Fig. 4a). The $EF$ is plotted in Fig. 14b. Finally, the junction temperature is determined from the relationship between the junction temperature and the $EF$ (Fig. 4b). The result is shown in Fig. 14c. The junction temperature remains nearly the same after 50,000 h.

4. Analysis of power electronics

The reliability of power electronics is critical to the operation of the synthetic jets and the LED light engine. The analysis of the power electronics in this section is limited only to the degradation mechanisms that cause output voltage drop; the breakages of other passive devices that cause catastrophic failure of the circuits is not considered.

4.1. Synthetic jet driving circuit

The synthetic jet driving circuit is a resonant circuit, which provides an excitation voltage of ±30 V at 175 Hz of frequency. The
piezoceramic disks in the synthetic jets act as one of capacitors in the circuit. The capacitance of the piezoceramic disk can be degraded over time \[16,17\], which in turn can change the operating voltage of the driving circuit.

The impedance of the resonant circuit can be expressed as:

\[
X_{\text{total}} = \sqrt{R^2 + \left(\frac{1}{2\pi f C_{\text{total}}}\right)^2}
\] (18)

where \(X_{\text{total}}\) is the impedance of the circuit in ohms, \(R\) is the resistance in ohms, \(f\) is the frequency in Hz, \(L\) is the inductance in henrys, and \(C_{\text{total}}\) is the total capacitance of capacitors in the circuit including the synthetic jet in farads. Then the current \((I)\) of the circuit is expressed as:

\[
I = \frac{V}{X_{\text{total}}}
\] (19)

where \(V\) is input voltage. Table 3 shows the actual values of the passives used in the circuit.

The applied voltage to the synthetic jet then becomes:

\[
V_{\text{jets}} = \frac{IX_C}{2\pi f C_{\text{total}}}
\]

\[
= \frac{V}{2\pi f(C_{\text{circuit}} + C_{\text{jets}})\sqrt{R^2 + \left(\frac{1}{2\pi f C_{\text{total}}}\right)^2}} - \frac{1}{2\pi f C_{\text{circuit}} + 2\pi f C_{\text{jets}}}^2
\] (20)

where \(V_{\text{jets}}\) is the applied voltage to synthetic jets and \(X_C\) is the impedance of the total capacitance.

The effect of the capacitance reduction of synthetic jets \((C_{\text{jets}})\) on the applied voltage \((V_{\text{jets}})\) is shown in Fig. 15. The initial capacitance of synthetic jets was 565 nF and the voltage was about 30 V. The result shows that the voltage remains about 30 V even when the capacitance of synthetic jets becomes 0. The capacitance degradation of the piezoceramic disk does not have a significant effect on the applied voltage in the synthetic jet.

### 4.2 LED driving circuit

An LED drive circuit is composed of many electronics components such as capacitors, diodes, resistors, inductors and transistor–transistor logic (TTL) devices. The most critical parts have been identified as electrolytic capacitors \[18–21\]. The effect of electrolytic capacitor degradation on the LED driving circuit is evaluated.
The LED drive circuit supplies a constant power to the LEDs, which are connected in series, set by the Discontinuous Conduction Mode (DCM) operation of the standard fly-back converter. Any fluctuation of the voltage output will thus affect the current through the LEDs. The current fluctuation can be estimated by the forward voltage and the current relationship assuming that the LED impedance remains constant over the range of voltage fluctuation. The major source of voltage fluctuation is the ripple voltage magnitude in the dc output.

The forward voltage oscillates between $V_{\text{max}}$ and $V_{\text{min}}$; the magnitude of ripple voltage, $V_r$ is $V_{\text{max}} - V_{\text{min}}$. The amount of ripple voltage can be estimated through the relationship between the capacitance and the ripple voltage, which is expressed as:

$$V_r = \frac{I}{2fC}$$

where $V_r$ is the ripple voltage, $I$ is the current, $f$ is the frequency, and $C$ is the capacitance of capacitors in the circuit. Then the average voltage ($V_{\text{ave}}$) can be expressed as:

$$V_{\text{ave}} = V_{\text{max}} - \frac{V_r}{2}$$

The capacitance degradation can be expressed as [23]:

$$C = C_0 \left( Ae^{t/t_1} + B \right)$$

where $C$ is capacitance, $C_0$ is initial capacitance, $t$ is time and $A$, $t_1$ and $B$ are constants. The data in Refs. [24] was also used as a conservative representation of the capacitance degradation. The percentage drop of the capacitance based on the function is shown in Fig. 16a.

The voltage applied to each LED can be estimated by

$$V_f = \frac{V_{\text{ave}}}{N}$$

where $V_f$ is the voltage drop across each LED and $N$ is the total number of LED in the circuit. The forward voltage decrease can be shown in Fig. 16b. The decrease of forward voltage can be converted to forward current reduction with the $V_f$ vs. $I_f$ relationship. If the data in Ref. [22] is used, the current decreases by about 5% while the capacitance decreases by 12%. Since the current reduction is not significant with this data, it will not be considered when the performance of the power electronics is to be evaluated in the PoF model.

5. Life time prediction

5.1. Lifetime of LED

Since the lifetime of a luminaire is governed by the lumen maintenance of LED, the LED lifetime directly affects the failure of a luminaire. In order to estimate the LED lifetime, major LED
5.2. Computation of luminaire lifetime

All the information for the computation of lifetime has been obtained in the previous sections. The purpose of experiments and calculations was to predict the decay constant profile with time by using the junction temperature and forward current prediction data. The luminaire lifetime can then be determined using the decay constant profile.

Fig. 18 summarizes the procedure to compute the luminaire lifetime. The left track shows all the processes from the amplitude degradation of the synthetic jet to the junction temperature. The amplitude degradation of the synthetic jet is first determined through the hybrid experiment/numerical model considering the compliant ring aging. The amplitude is converted to the air flow rate (Eq. (4)). Then the junction temperature is determined as a function of time using the empirical relationship between the enhancement factor and the junction temperature (Fig. 4b).

The right track deals with the issues associated with the driver electronics. The increase in the ripple voltage, caused by the capacitance degradation of the electrolytic capacitors in the LED driving circuit, is determined as a function of the operating time using the data in Ref. [23]. Then the reduction of the forward current is subsequently determined from the relationship between the forward current and forward voltage.

From Eq. (2), the decay constant for a given junction temperature and a forward current can be expressed as:

$$\alpha(T_j, I_f) = \frac{1}{t_{70}(T_j, I_f)} \ln 0.7$$

where $t_{70}$ is the time at the lumen maintenance of 0.7.

The junction temperature will rise with time, which can be expressed in a general form as $T_j(t) = T_j^0 + K(t)$ where $T_j^0$ is the initial junction temperature and $K(t)$ is a function that defines the junction temperature increase as a function of time. The forward current will decrease with time, which can also be expressed as $I_f(t) = I_f^0 + I(t)$ where $I_f^0$ is the initial forward current and $I(t)$ is a function that defines the forward current decrease as a function of time.

As illustrated in Fig. 19, the lumen maintenance after each small time interval of $\Delta t$ can be expressed as:

$$L_k = L_0 \exp \left\{ -\Delta t \sum_{i=1}^{k} \alpha(T_j^i, I_f^i) \right\} \quad \text{for } k = 1, 2, 3, \ldots$$

where

$$T_j^i = T_j^0 + \frac{T_j^i(k-1)\Delta t}{2} + T_j^i(k\Delta t)$$

$$I_f^i = I_f^0 + \frac{I_f^i(k-1)\Delta t}{2} + I_f^i(k\Delta t)$$

where $L_0$ is the lumen maintenance after the $k$th time interval; $T_j^i$ is the averaged junction temperature over the $k$th time interval; $I_f^i$ is the averaged forward current over the $k$th time interval; $L_0$ is the initial lumen output at time zero. It is worth noting that the function, $K(t)$, is directly related to the time-dependent performance degradation of the active cooling system (i.e., $EF$ reduction). The function, $I(t)$, in the computation is 0 due to the small amount of reduction of the current and thus $I_f^i$ is constant (500 mA). Then the lifetime criterion can be expressed as:

$$0.7L_0 \geq L_k$$

If $\Delta t$ is set, the unknown “$k$” can be determined. In practice, the optical component degradation in the fixture as a function of temperature is ignorable. Then the final expected life at 70% luminaire maintenance can be determined as
The decay constant for each time interval can be computed by Eq. (25). The result is shown in Fig. 20. Then, the lumen maintenance is calculated by Eq. (26). Fig. 21 shows the final result. Based on this calculation, the lumen maintenance is estimated to be 76% after 50,000 h operation.

6. Conclusion

A physics-of-failure based, hierarchical reliability model was implemented to determine the lifetime of an Edison base – 6 in., compatible can, downlight – LED replacement bulb, cooled by synthetic jets. The degradation mechanisms of each of the main components (LED light engine, cooling system, and power electronics) were analyzed and their combined effect on luminaire reliability was calculated. The degradation rate of the synthetic jet was extremely low and the junction temperature rise over the intended life (50,000 h) was negligible. For the power electronics, only time-dependent degradation of large electrolytic capacitors was considered and its effect on an increase in ripple voltage was estimated using the existing data in the literature. Based on the proposed hierarchical model, the lumen maintenance was estimated to be 76% after 50,000 h operation.

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