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CAE Application in Automotive Lighting

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Abstract

This paper proposes an application of CAE technology in automotive lighting design. Firstly, the thermal performance of a simple lighting system, similar to automotive forward projector was predicted by using a finite element analysis. The multiphysics analysis was employed to account for heat transfer mechanism and thermal deformation in the lighting system. Next, the beam pattern and irradiance of the lighting system was predicted by using a ray tracing method. The beam shift due to the thermal deformation of reflector and lens was also presented. With the finite element and ray tracing methods, the thermal performance and beam quality of the lighting system can be assessed in the early design stage prior to the costly prototype fabrication. Furthermore, the conceptual methodology gained from this paper can be applied on other automotive lighting systems, especially headlamp or fog lamp, for soothing the beam shift problem, which is taken seriously into account as a key criterion in automotive lamp design.

Keywords: Multiphysics Analysis, Finite Element Method, Ray Tracing Method, Automotive Lamp

1. Introduction

To comply with the international automotive standards such as ECE, SAE or JIS, all automotive lamps must be tested to assess their thermal and optical performance during its operation. Therefore, engineers who design automotive lamps must carefully consider in two main criteria, which are the thermal behavior and beam quality of those lamps. These two criteria are much more crucial for headlamp and fog lamp design, where the optics moves from lens to reflector surface, because the high temperature of the bulb in headlamp can cause the thermal deformation of reflector and lens which introduces a severe beam shift problem.

To predict the thermal behavior and beam quality of virtual headlamp prototype on personal computer, finite element and ray tracing method are introduced for automotive lamp design and analysis. By combining these two CAE technologies, engineers can develop headlamp design guidelines without the costly fabrication and testing of multiple physical prototypes.

In this paper, the predictive methodology for an automotive lighting design process was presented. A simple automotive projector with a polyetherimide (PEI) thermoplastic reflector and a polycarbonate lens was used as a study case. An initial geometry and beam pattern of the simple projector was obtained by using a ray tracing method. Next, the finite element thermal model was developed to predict the temperature distribution and thermal deformation at reflector and lens instead of those costly and time-consuming experimental trials and errors. The multiphysics analysis (fluid flow coupled with heat transfer) was used to account for heat transfer mechanism in the lighting system, which are conduction, convection and radiation within the housing, conduction through reflector and lens, and external convection loss. Then, the deformed geometry was exported to predict beam pattern by ray tracing analysis and compared to the beam pattern of an initial design. According to the analysis, the predicted thermal distribution and beam pattern results can provide needed information for engineers to evaluate the thermal and optical performance of automotive lighting systems prior to building prototypes and continue on photometric and thermal tests in a laboratory.

2. Theory

2.1 Fluid Flow and Heat Transfer

The fluid flow and heat transfer theories in this paper can be divided into 3 main parts, as described below;

2.1.1 Conduction through the reflector and bulb surface

For the conduction, the governing equation for solving the local temperature [1] is,

$$-k\nabla T \bullet \mathbf{n} = q_a + q_r + q_c \tag{1}$$

where k is the thermal conductivity, q_a is the applied heat flux, q_r is the radiative heat flux, q_c is the convective or conductive heat flux, and T is the local temperature.

2.1.2 Convection within the enclosure and outside the external environment

The governing equations of fluid flow for the enclosed air and heat transfer equations for heat that convects to the external environment will be presented.

2.1.2.1 Within the enclosure, the equations governing the laminar steady flow of an incompressible viscous fluid have to relate on the conservation of mass, momentum, and energy. Moreover, the buoyancy force is added in the momentum equation according to the Boussinesq approximation [2].

Mass Balance Equation

$$\nabla \bullet \mathbf{v} = 0 \qquad (2)$$

where $\mathbf{v}$ is the velocity vector.

Momentum Balance Equation

$$\rho_0 \mathbf{v} \cdot \nabla \mathbf{v} = -\nabla p + \mu \nabla^2 \mathbf{v} - \rho_0 \left[\beta_T \left(T - T_0\right)\right]\mathbf{g} \qquad (3)$$

where ρ_0 is the fluid density at reference temperature T_0, p is the pressure, μ is the dynamic viscosity, β_T is the thermal expansion coefficient, and $\mathbf{g}$ is the acceleration vector due to gravity.

Energy Balance Equation [1]

$$\rho_0 c_p \mathbf{v} \cdot \nabla T = k \nabla^2 T \qquad (4)$$

where c_p is the specific heat of fluid and k is the thermal conductivity of fluid.

2.1.2.2 External convection by Newton's law of cooling [2 pp.2]

$$q_c = h_c \left(T - T_\infty\right) \qquad (5)$$

where h_c is heat transfer coefficient and T_∞ is reference temperature. At ambient temperature of 35°C, the heat transfer coefficient is 7.9 W/m^2

Table 1 Thermophysical properties required for the thermal analysis

Properties	PEI	PC	Air
ρ_0 (kg/m^3)	1270	1200	0.746
k (W/m/K)	0.22	0.19	0.0378
c_p (J/kg/K)	1100	1250	1027
μ (kg/m/s)	-	-	0.0000258
β_T (K^{-1})	-	-	0.00211

2.1.3 Radiation in the enclosure and around the external environment by Stefan-Boltzman law [3]

$$q_r = se\left(T^4 - T_\infty^4\right) \qquad (6)$$

where $s = 5.67 \times 10^{-8}$ W/m^{2}K^4 is the stafan-Boltzman constant and $e = 0.9$ is the emissitivity

2.2 Solid Mechanics

In this paper, the homogeneous, isotropic and linear materials are presented. The governing differential equations of axisymmetric problem for equilibrium conditions [1] are,

$$\frac{\partial \sigma_r}{\partial r} + \frac{\partial \tau_{rz}}{\partial z} + \frac{\sigma_r - \sigma_\theta}{r} + F_r = 0 \qquad (7a)$$

$$\frac{\partial \tau_{rz}}{\partial r} + \frac{\partial \sigma_z}{\partial z} + \frac{\tau_{rz}}{r} + F_z = 0 \qquad (7b)$$

where σ_i is the normal stress in *i*-direction, τ_{ij} is the shearing stress in *ij*-plane and F_i is the force vector in *i*-direction.

The strain-displacement relationships are given by,

$$\{\bar{\delta}\} = \begin{Bmatrix} u \\ w \end{Bmatrix} \qquad (8)$$

$$\{\varepsilon\} = \begin{Bmatrix} \varepsilon_r \\ \varepsilon_\theta \\ \varepsilon_z \\ \gamma_{rz} \end{Bmatrix} = \begin{Bmatrix} \frac{\partial u}{\partial r} \\ \frac{u}{r} \\ \frac{\partial w}{\partial z} \\ \frac{\partial u}{\partial z} + \frac{\partial w}{\partial r} \end{Bmatrix} \qquad (9)$$

where $\{\delta\}$ is the displacement vector, u is the displacement in radial direction, w is the displacement in z direction, and $\{\varepsilon\}$ is the strain vector

The stress-strain relationship may be written in matrix form as,

$$\{\sigma\} = [C]\{\varepsilon - \varepsilon_0\} \qquad (10a)$$

where

$$[C] = \frac{E}{(1+\nu)(1-2\nu)} \begin{bmatrix} 1-\nu & \nu & 0 & 0 \\ \nu & 1-\nu & \nu & 0 \\ 0 & \nu & 1-\nu & 0 \\ 0 & 0 & 0 & \frac{1-2\nu}{2} \end{bmatrix} \qquad (10b)$$

$$\{\sigma\}^T = \lfloor \sigma_r \quad \sigma_\theta \quad \sigma_z \quad \tau_{rz} \rfloor \qquad (10c)$$

$$\{\varepsilon\}^T = \lfloor \varepsilon_r \quad \varepsilon_\theta \quad \varepsilon_z \quad \tau_{rz} \rfloor \qquad (10d)$$

and

$$\{\varepsilon_0\} = \lfloor \alpha \Delta T \quad \alpha \Delta T \quad \alpha \Delta T \quad 0 \rfloor \qquad (10e)$$

where $[C]$ is the elastic modulus matrix, and $\{\varepsilon_0\}$ is the initial strain vector.

2.3 Ray Tracing

In ray tracing method, light is considered as an electromagnetic wave traveling through space. A light ray is defined as a line normal to the direction of wave propagation [4]. A light ray or ray obeys the laws of geometrical optics and can be transmitted, reflected, and refracted through an optical system following the Snell's law [5] as described below,

$$n_1 \sin\theta_1 = n_2 \sin\theta_2 \tag{11}$$

where n_1 and n_2 are the refractive indices of medium 1 and 2, respectively, θ_1 is the incident angle of light ray with respect to the normal, and θ_2 is the refracted angle.

After, the ray paths from light bulb to detector are determined, the flux or energy per unit time of each ray will be calculated. Flux is the time rate change of energy and can be defined by [6],

$$\phi = \frac{dQ}{dt} \tag{12}$$

where Q is the radiant energy of light.

Ray tracing for an automotive lamp analysis is based on a calculation of flux for each ray following the determined ray paths. When the light passes through an object. Some of all flux will be absorbed. The flux of transmitted light can be calculated by [5],

$$\phi = \phi_0 e^{-\alpha x} \tag{13}$$

where ϕ is the intensity of transmitted light, ϕ_0 is the intensity of light entering the material, α is the absorption coefficient of material, and x is the thickness of the object.

At the detector, the irradiance or radiant incident (E) of the ray can be calculated by [6],

$$E = \frac{d\phi}{dA} \tag{14}$$

where A is the area of the detector surface.

3. Computational Procedure

The computational procedure for predicting thermal performance and beam quality of automotive lighting application is shown in Figure 1. Generally, at the beginning of the design process, the initial geometry of reflector and lens are commonly obtained by using a ray tracing analysis. Then, the thermal performance and deformation are usually tested later by trial and error experiments. For this paper, the thermal performance and deformation of reflector and lens will be predicted by using finite element method instead of those costly and time-consuming trial and errors. The thermal behavior inside the lighting system can be analyzed by finite element model, which capable of simulating fluid flow coupled with conduction, convection and radiation. Next, the thermal distribution result will be applied as a thermal load for structural analysis to obtain the deformed geometry of reflector and lens. Finally, the beam pattern of deformed geometry will be predicted by using the ray tracing method and compared to the beam pattern of an initial geometry to assess the beam quality.

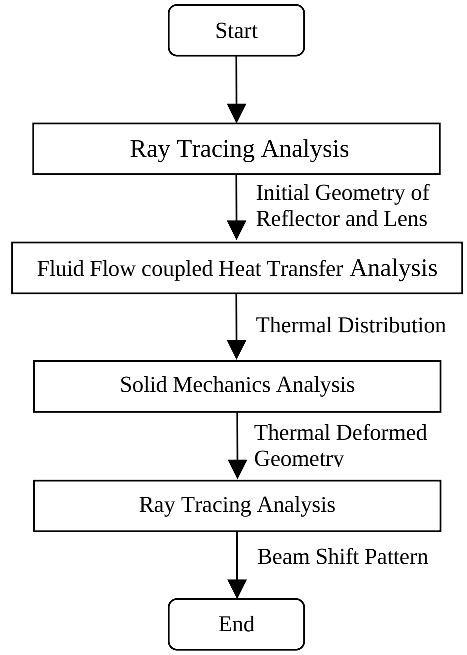

Figure 1. Computational Procedure for Automotive Lighting Analysis

4. An application on Simple Automotive Lamp

The formulations and the computational procedure described in the previous section were used for predicting thermal performance and beam quality of a simple automotive lighting system. By using the ray tracing method, the initial geometry of a simple lighting system was designed and its optical property, such as reflectance and transmittance was applied to predict the beam pattern. The lighting system consists of the 5 mm.- thick polyetherimide (PEI) elliptical reflector part, the polycarbonate (PC) lens with 5 mm. in thickness, and the 60 watts illuminated lamp bulb at an operating condition of 12.8 Volts. The CAD model of this lighting system was shown in Figure 2.

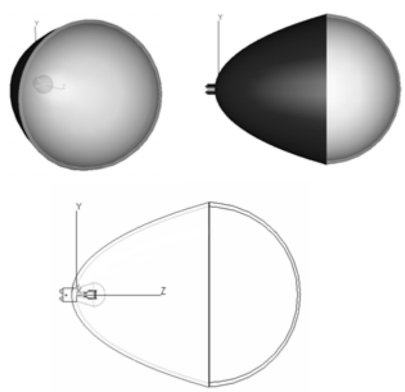

Figure 2. CAD Model of the Lighting System

For thermal analysis, the 2D finite element model of air within the enclosure, reflector and lens were built by using an axisymmetric element type due to the symmetry of the lighting system's model as illustrated in Figure 3.

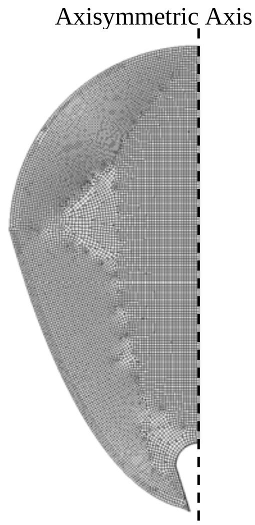

Figure 3. Finite Element Model of the Lighting System

The reflector and lens part were modeled as solids that transport energy by conduction. Within the enclosure, the computational fluid dynamics was applied to analyze velocity and temperature of the enclosed air. The air was modeled as an incompressible viscous fluid that encounters flow caused by the buoyancy force and transports energy by conduction, convection and radiative heat transfer. A no slip condition was applied along the bulb surface and internal surface of the lamp.

The light bulb was replaced by its surface contour in the finite element model with a heat flux boundary condition. The bulb and inner surface of reflector and lens was coupled with the energy balance equation for the air through heat flux boundary condition to calculate the radiant heat exchange.

At the outer surface of the reflector and lens, heat was naturally convected to the ambient air. The finite element model and the boundary conditions as described above were applied for the heat transfer analysis.

Calculation of heat transfer process starts from the lamp bulb. A heat source for this system is the heat flux generated from the 60 watts light bulb. The heat at the bulb surface transfers to the enclosed air so that, the air closed to the bulb has the higher temperature than others. In general, this higher temperature air will move up, while the lower will move down. This causes the recirculation zone due to the change of an airflow pattern.

Next, heat from the enclosed air and bulb surface is partially transferred to the internal surfaces of reflector and lens. That heat is transferred through the reflector and lens part by conduction and then convects to the external ambient air. The heat radiation within the lighting system is taken into account simultaneously.

According to the fluid - thermal coupled analysis results, the predicted airflow passage and the calculated temperature distribution of the reflector and lens is shown in Figure 4 and 5, respectively.

Figure 4. The Recirculation Zone within Lighting System

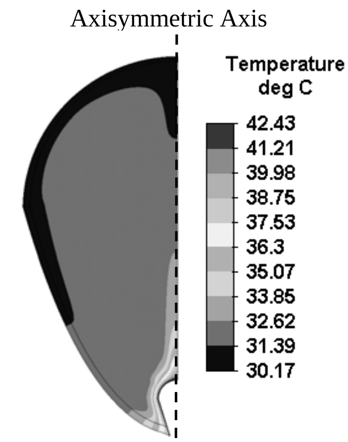

Figure 5. The Predicted Temperature Distribution

By using the structural analysis, the thermal distribution result was used as a thermal input load for calculating thermal deformation of reflector and lens. The predicted result in Figure 6 shows that the maximum displacement of this lighting system is about 50 microns and occurs at the polycarbonate lens.

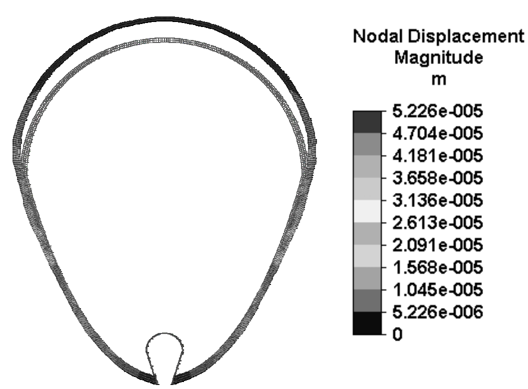

Figure 6. The Predicted Thermal Deformation

In ray tracing analysis, The PEI reflector surface was assumed to be an aluminized surface that reflects light at 96 percent. The polycarbonate lens has index of refractive at 1.591 and transmits light at 98 percent. A 500x500mm^2 detector locates at the focus of reflector. The surface of reflector and lens is assumed to be a well-polished surface to neglect the effect of scattering. The ray paths from light bulb to detector will be figured out as shown in Figure 7.

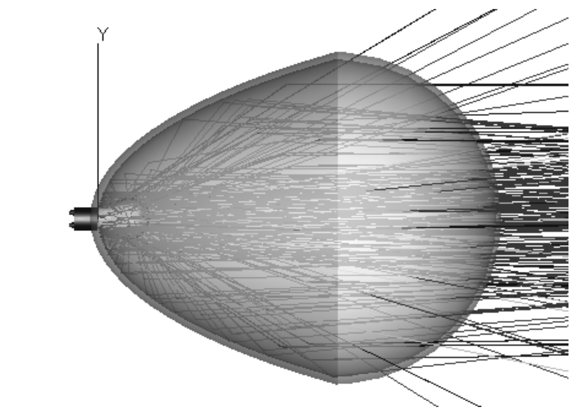

Figure 7a. The Predicted Ray Paths within the Lighting System

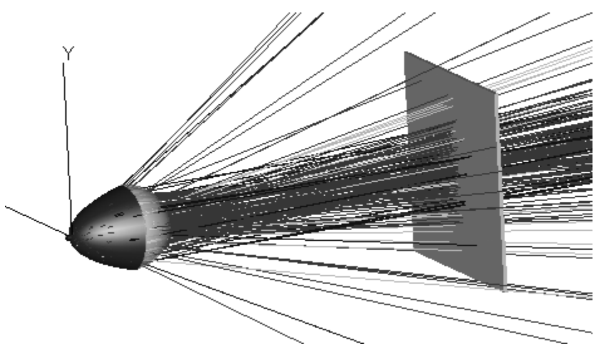

Figure 7b. The Predicted Ray Paths from the Lighting System to Detector

When comparing the beam pattern of initial and deformed geometry, the results show that light from the deformed geometry was shifted and the maximum irradiance reduces from 8,000 to 2,090 W/m^2 as shown in Figure 8. With the displacement magnitude in microns, the direction of light is deflected from the focus and directly affects the beam pattern and irradiance of the lamp. This beam shift due to thermal deformation can be a serious problem in a cut off beam test for an automotive forward lighting, which the beam pattern and illumination are measured as critical to quality parameters.

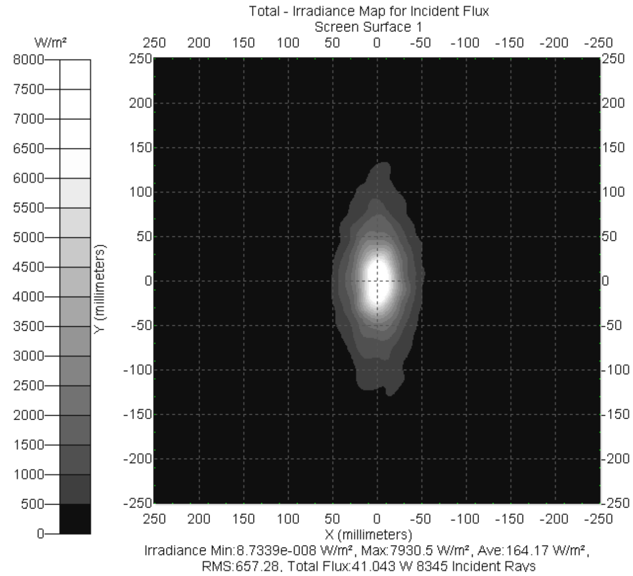

Figure 8a. The Predicted Beam Pattern of an Initial Geometry

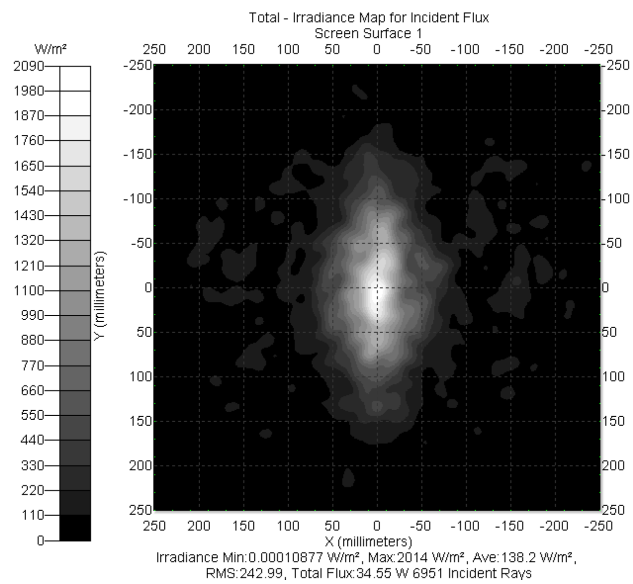

Figure 8b. The Predicted Beam Pattern of a Deformed Geometry

5. Conclusion

In this paper, the predictive methodology for automotive lighting design was developed. The finite element thermal model for a lighting system was built to predict the thermal behavior due to conduction, convection and heat radiation within the lamp. The temperature distribution on reflector, lens and enclosed air were calculated by coupling the fluid flow and heat transfer analysis. With the same thermal model, the thermal deformation of reflector and lens was predicted by using the thermal distribution result as a thermal load for structural analysis. The thermal results can be used as a guideline for material selection or venting design of the lamp.

By integrating with ray tracing analysis, optical engineers can evaluate the beam shift due to the deformation of reflector and lens surfaces caused by excessive thermal from the light bulb. This information can facilitate automotive lamp engineers in beam quality assessment and give them a clue for optical redesign.

With the available CAE technologies, the thermal and optical performance of an automotive lighting system can be predicted in the design step without the costly fabrication and testing of multiple prototypes. The information gained from the finite element and ray tracing method can give engineers the suggestive information and insights into the important factors in automotive lamp design. Furthermore, the predictive methodology of this paper can be applied on other complex automotive lighting systems, especially headlamp or fog lamp, which operate at a very high temperature.

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References

[1] P. Dechaumphai, Finite Element Method in Engineering, Third Ed., Chulalongkorn University Press, Bangkok, Thailand, 2004, pp. 261-263, 217-220

[2] W.M. Kays and M.E. Crawford, Convective Heat and Mass Transfer, Third Ed., McGraw-Hill, Inc., Singapore, 1993. pp. 398

[3] R. Siegel and J. R. Howell, Thermal Radiation Heat Transfer, Second Ed., Hemisphere Publishing Corporation., USA., 1981. pp. 31

[4] A. Walther, The Ray and Wave Theory of Lenses, First Ed., Cambridge University Press, Cambridge, UK, 1995, pp. 283-285.

[5] E. Hecht, Optics, Fourth Ed., Addison Wesley, San Francisco, USA, 2002, pp. 87-103, 128

[6] J. B. Murdoch, Illumination Engineering – From Edison's Lamp to the Laser, First Ed., Macmillan Publishing Company, New York, USA, 1985, pp. 27-35