Electrostatically actuated window blinds

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Abstract

An electrostatic method for actuating window blinds was recently developed by the authors in work that is documented elsewhere. The method was developed in an experimental effort without the help of predictive tools. This paper examines that problem in more detail and formulates an electrostatic model for these systems. The complexity of the charge distribution over the slats and the glass demands a relatively large model (hundreds of thousands of degrees of freedom). This paper formulates the large-order model and then shows how to reduce the order of the model significantly. The charge distribution is represented as a linear combination of assumed modes. The charge distribution is assumed to be periodic in the vertical direction, which is tantamount to neglecting end effects. Experimental results verify the accuracy of the predictions in the presence of the order-reduction assumptions. The electrostatic model predicts the slat angles to within the accuracy of the measurement system. The conductive and convective heat transfer across the air space are also analyzed. The flow patterns explain the heat transfer (thermal efficiency) of windows with slats enclosed. © 2001 Elsevier Science B.V. All rights reserved.

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1. Introduction

Recently, the architectural community has realized the importance of using natural light in new building construction (daylighting). It has been proven that natural light is essential for the health, well-being, and productivity of individuals [1]. Energy
the coated side facing away from the window (see Fig. 1). In the absence of static electricity, the gravity force acting on the slats causes them to rotate to a closed vertical position. When electrostatic charge (in the form of a dc voltage difference relative to ground) is applied to the slats, opposing charge builds up on the low-e glass, causing the slats to be attracted to the grounded low-e glass and repelled from one another (electrostatic induction). The slats then rotate open toward the low-e glass [5]. To increase the electrostatic force, low-e glass could also be used on the opposite side of the window. However, in the interest of simplicity and lowering expense, it is only used on the glass surface facing the interior of the building. Ordinary glass is used for the other side.

The design development of the blinds was largely experimental, so very little analysis was done during development to quantify the electrostatic forces. In order to achieve a better understanding of the electrostatic forces, and in order to determine the voltage necessary to achieve desired slat angles, an electromechanical analysis of a vertically mounted blind is presented in this paper. It is also common practice to mount windows at an incline (skylights for example), and the modeling presented here could easily be adapted to handle this situation. However, in the interest of presenting a concise analysis only the results of vertically mounted windows are presented.

The electromechanical analysis of the blind is presented in the first section of this paper. Computer modeling is used to predict the electrostatic and gravitational forces present, thus determining the slat angles in relation to the applied voltage. The theoretical results are compared to values measured using an experimental window, and the results are presented in the discussion section.

Powerblinds lend themselves well to automatic control, and they can be operated to provide optimal radiative heating and daylighting. However, it was not previously known what effect the blind slats had on the convective heat transfer in the air space. The second section of this paper presents the conservation equations needed to determine the convective heat transfer. Because of the complex geometry caused by the inclusion of the slats in the air space, the convective heat transfer is calculated using a finite element model, rather than trying to find a closed form solution. The convective heat transfer for a window without blinds is compared to a window with blinds at four different slat angles. The convective heat transfer results, calculated using a finite element method, are presented in the discussion section of this paper.

2. Electromechanical analysis

Consider the blind cross section shown in Fig. 1. The slats and the low-e glass surface are electrically conductive. A dc voltage \( V \) is applied to the electrically connected slats and the low-e glass surface is grounded (ac voltage could also be used, but the authors did not explore this possibility). These voltages cause a build-up of electrostatic charge on the slats and the glass. The relationship between the applied voltages and the electrostatic charges is determined by an electrostatic analysis. The electrostatic charges on the slats and the glass produce an electrostatic moment on the
Eq. (2) is used to determine the charge distributions for a given voltage as a function of the blind slat angle. Coulomb's law is then used to determine the electrostatic forces and resulting moments acting on the slats. The blind slat angles are then determined in an iteration. The slat angles are varied until the electrostatic moment and the gravitational moment (due to the slats off-set axis) balance.

2.2. Calculation of electrostatic forces

To perform the iterative analysis, a computer code was written for Matlab to perform the iterations necessary for determining slat angles. The theoretical charge distributions and corresponding slat angles were determined for the window at five different voltages. The dimensions of the window (Fig. 2) were as follows: $d_1 = 6.41 \text{ mm}$, $d_2 = 9.59 \text{ mm}$, $d_3 = 14.28 \text{ mm}$, and $d_5 = 12.7 \text{ mm}$. The slat thickness was 0.2 mm. The theoretical slat angles were compared to an experimental window setup with the same applied voltages. The experimental setup used simple trigonometry to determine the slat angles. A measurement scale was printed on a vertical surface a few feet behind the window. A visual projection onto the vertical scale, along with the distance to the vertical surface, could then be used to determine the slat angle (Fig. 3). For the experimental setup, 10 different slats were measured at each voltage, and the average and standard deviation of the 10 slat angles at each voltage were calculated. The average values were then compared to the theoretical values calculated by the Matlab code.
3.1. Air space convection theory

In insulated glass, the thickness dimension is small compared to the width and height dimensions. Consequently, the thermal analysis of the powerblind can treat the blinds as an infinite system in the $y-z$ plane, where the thermal variables are assumed to be periodic. These assumptions have been shown to be valid for height-to-air-space ratios greater than 36 [9]. For the powerblind air space, windows greater than 0.7 m high will conform. Only the heat transferred by convection will be considered in this work. The radiative heat transfer is not negligible, but it takes place independently of the convective heat transfer and is beyond the scope of this analysis.

It has been accepted that the optimum size of a vacant airspace is approximately 19 mm. In a smaller airspace, conduction through the thickness dominates the heat transfer. In a larger airspace, convection parallel to the glass plane, most of which flows up and down, dominates the heat transfer [9].

Letting $T_0$ and $T_1$ denote the absolute temperatures of the glass interior at the left and right boundaries and recognizing that the difference between these absolute temperatures is very small compared to $T_1$, it follows that this temperature difference can be neglected in the thermal analysis for all purposes except for calculating the buoyancy force (the Boussinesq approximation — Ref. [10]). At any point in the airspace, the non-dimensional change in the fluid mass density $\rho$ is then equal to the negative of the non-dimensional change in the absolute temperature $T$ [9], that is

$$\frac{\rho - \rho_0}{\rho_0} = -\frac{T - T_0}{T_0}. \quad (4)$$

With these assumptions, the condition for incompressibility, the equation of state, and the Navier–Stokes force equations, taking into account the buoyancy forces and assuming steady-state conditions, are given by [9]

$$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} = 0, \quad (5)$$

$$u \frac{\partial \theta}{\partial x} + v \frac{\partial \theta}{\partial y} = \kappa \left( \frac{\partial^2 \theta}{\partial x^2} + \frac{\partial^2 \theta}{\partial y^2} \right), \quad (6)$$

$$u \frac{\partial v}{\partial x} + v \frac{\partial v}{\partial y} = -\frac{1}{\rho_0} \frac{\partial p}{\partial y} + G \left( \frac{\rho - \rho_0}{\rho_0} \right) + \nu \left( \frac{\partial^2 v}{\partial x^2} + \frac{\partial^2 v}{\partial y^2} \right), \quad (7)$$

$$u \frac{\partial u}{\partial x} + v \frac{\partial u}{\partial y} = -\frac{1}{\rho_0} \frac{\partial p}{\partial x} + \nu \left( \frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 u}{\partial y^2} \right). \quad (8)$$

The boundary conditions imposed at the vertical boundaries and on the slats are as follows [11]:

$$u = v = 0, \quad \theta = 0 \quad \text{at} \quad x = 0,$$

$$u = v = 0, \quad \theta = 1 \quad \text{at} \quad x = d,$$

$$u = v = 0 \quad \text{at the slat boundaries.} \quad (9)$$
the slats as shown. Notice, as expected, the charges are highest on the slats and the grounded glass where the two surfaces are closest to each other. Also, as expected, an increase in voltage corresponds to an increase in the charge build-up causing the slats to open farther. Finally, edge effects can be observed in the slat charge distribution graphs at the edge farthest from the grounded glass. In all, the theoretical predictions match what one would expect to see from the application of an electrostatic charge to the geometry of the window.