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A2_7 Slamming doors due to open windows

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Abstract

The force required to close a door in a small room with a window open can be observed to be less than that required if the window is shut, this is due to the behaviour of air around the door as it is closed. This paper presents a model for this phenomena. It is found that the forced flow of air around the door is the major cause of the effect. The movement of the door when closing is barely changed until the door has nearly closed, at which point the force retarding the door increases substantially.

Introduction

A commonly observed phenomena is that the force required to close a door in a room is reduced when a window in the room is open. This can lead to the door slamming if the reduced force requirement is not considered. This paper presents a model to explain this phenomena.

Theory

As a door is closed the conditions of the air in its environment change in several ways. When all windows are closed, air leakage out of the room will be minimal, assuming the room is not too large. As the door is closed, the air in front of the door is forced out of the door's path, creating an area of high pressure; the area swept out by the door is left with less air, creating an area of low pressure behind the door. At room temperature the air moves quickly to equalise the pressures in these areas, resulting in a flow of air from the area of high pressure in front of the door to the area of low pressure behind the door. Additional force is required to shut the door as the air must be pushed out of its path.

In the case where the door connects a small room, such as a bedroom, and a large room, such as a hallway, the larger volume of air in the large room can adjust to allow the high pressure air in front of the door to move out of the way. However, the low pressure area behind the door draws air from in front of the door in a similar fashion to before, allowing this difference to be ignored.

When a window is open in the room, the pressure differences created by closing the door do not need to be equalised by the movement of air around the door. Air can flow in through the window to equalise the pressure behind the door. The air requires far less force to move, so the force required to close the door is reduced.

In this model it is assumed there is no flow through the window due to outside wind and the only difference in the case where the window is open is the change in pressure balancing by the air.

Closing the door without air resistance

Assuming that a reasonable time to close a door is 1 second and that to close the door a constant force is applied, the force required can be determined. Assuming that the handle is located at the edge of the door furthest from the pivot, the force to close the door is

$$F_{\mathrm{rot}} = \frac{\tau}{w}, \tag{1}$$

where τ is the torque required and w is the width of the door. The torque required is given by

$$\tau = I\alpha, \tag{2}$$

where I is the moment of inertia of the door and $\alpha = 2\phi/t^2$ is the angular acceleration, where $t = 1\,\mathrm{s}$ is the time taken and $\phi = \pi/2$ rad is the angular displacement, assuming the door is initially open at 90°. Therefore $\alpha = \pi$ rad s^{-1}. The moment of inertia is found using the integral

$$I = \int_V \rho r^2 dV = \frac{m}{hw\delta}\int_0^w\!\!\int_0^\delta\!\!\int_0^h r^2\,\mathrm{d}z\,\mathrm{d}y\,\mathrm{d}x = \frac{1}{3}mw^2, \tag{3}$$

where V is the volume of the door over which the integral is taken, ρ is the door's density, r is the distance from the axis of rotation to a given point in the volume and m, h and δ are the mass, height and thickness of the door respectively. The coordinate system is defined such that the width, thickness and height of the door are in the x, y and z directions respectively. It is assumed the door is thin enough that the distance from the pivot to any point is independent of position in the y direction. This moment of inertia is equal to that of a thin uniform rod rotating about one end, it is independent of height and thickness.

Eq. (1) becomes

$$F_{\mathrm{rot}} = \frac{\pi}{3}mw. \tag{4}$$

A standard sized door is $1.98\,\mathrm{m} \times 0.762\,\mathrm{m} \times 35\,\mathrm{mm}$ [1], assuming the door is constructed with pine, the density will be $\rho \approx 530\,\mathrm{kg\,m^{-3}}$ [2]; this gives a door mass of $m = 28.0\,\mathrm{kg}$. The force required to move the door without air resistance is then $F_{\mathrm{rot}} = 22.3\,\mathrm{N}$.

Air resistance
Air will move freely from an area of high pressure to an area of lower pressure if not constrained, in the case of closing the door the air will prefer to flow from the area of high pressure in front of the door to the area of low pressure behind the door. Because of this flow, a minimal amount of air will flow through the door frame while the door is being closed. It is assumed that there is no flow through the door frame, and as such it can be considered a boundary. Due to this assumption the region between the door and the frame can be considered as a partly sealed volume of air, which is forced out as the volume of the region is reduced by the door closing.

Assuming the door is close enough to the floor that a negligible amount of air will flow underneath, the air forced out of the volume can flow out through the top or side. For the purpose of determining the area through which air can flow, the volume between the door and the door frame is treated as a triangular prism. When the door is open at an angle θ, the top of the volume is a triangle of area $w^2 \sin\theta$ and the open side of the volume has an area of $2hw\sin(\theta/2)$, the total area through which the air can flow is therefore $A = w\,[w\sin\theta + 2h\sin(\theta/2)]$.

The total air flow rate through this area can be determined by considering the volume of air displaced by the movement of the door. Since the door starts at an angle of 90°, the volume swept out during the 1 second to close is $Q = 1/4\pi hw^2$, which is also the total flow rate. The flow velocity is therefore

$$v = \frac{Q}{A} = \frac{\pi hw}{4\,[w\sin\theta + 2h\sin(\theta/2)]}. \tag{5}$$

Using Bernoulli's equation [3], the additional force required on the door to push air out from the volume can be determined. The pressure inside the volume is given by the sum of the atmospheric pressure P_{a} and the pressure applied by pushing the door. The pressure outside the volume is just P_{a}. Assuming the air velocity inside the volume is negligible, Bernoulli's equation along a streamline passing from the inside of the volume to outside the volume becomes

$$\frac{F_{\mathrm{air}}}{hw} = \frac{1}{2}\rho v^2, \tag{6}$$

where $\rho = 1.21\,\mathrm{kg\,m^{-3}}$ is air density at room temperature [4]. Therefore by substituting from Eq. (5), the additional force needed to push the door is

$$F_{\mathrm{air}} = \frac{1}{32}\pi^2 h^3 w^3 \rho\,[w\sin\theta + 2h\sin(\theta/2)]^{-2}, \tag{7}$$

which is plotted in Fig. 1. The plot shows that the effect of air resistance is negligible until the door is nearly closed (θ is very small), the additional force to close the door then increases rapidly. F_{air} becomes greater than F_{rot} for $\theta < 5°$, at this point the door becomes difficult to close quickly.

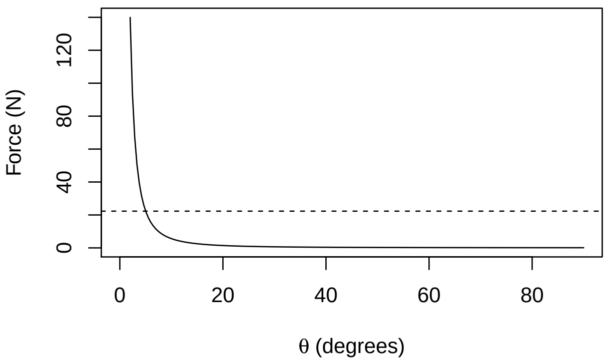

Fig. 1: Plot of Eq. (7). The solid line is the force to overcome the air resistance, the dotted line is the force required to move the door without including air resistance.

Conclusion
The model used successfully describes the observed behaviour of doors as they are closed. When the windows in a small room are shut, the effect of displacing air as the door is pushed makes the door more difficult to push when it is nearly closed. This effect of increasing resistive force means that doors are more difficult to slam, this is why when pushing a door and allowing it to swing, the door may sometimes stop just before it closes completely. If a window is opened in the room, the area of low pressure behind the door can be equalised by the outside air and therefore the air does not need to flow around the door. The effect of air resistance is then greatly reduced and the door can swing shut easily.

The model is idealised and in reality the system is able to leak air, because of this the force required to overcome the air resistance will be lower than determined here and will not increase asymptotically as the model suggests. The model also ignores a further effect due to air moving through the gap between the door and the door frame, the air movement causes a decrease in pressure in that area, which would apply a force on the door to shut it. It is this effect that causes nearly closed doors to slam if there is a draught.

References

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