Azerbaijan University of Architecture and Construction
ISSN 2706-7726

Engineering Mechanics
Scientific and Technical Journal

E-mail: engineeringmechanics@azmiu.edu.az

September 2025 | Issue 21 | Volume 13 | Number 3 | Pages 21-26

TRANSIENT MECHANICAL BEHAVIOR OF VENTILATION SYSTEMS SUBJECT TO OCCUPANCY-DRIVEN OPERATION USING ULTRASONIC DOOR-FRAME DETECTION

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Abstract: Ventilation systems operating under variable occupancy conditions are subject to repeated changes in mechanical loading, resulting in time-dependent dynamic behavior that is often neglected in conventional steady-state analyses. This study investigates the mechanical response of an occupancy-regulated ventilation system using ultrasonic door-frame detection. Occupancy variations are translated into discrete operational state transitions, producing acceleration and deceleration phases governed by rotor inertia and resistive effects. A lumped-parameter rotational model is developed to describe the transient behavior of the ventilation unit under stepwise torque changes. Time-domain simulations are performed to analyze angular velocity evolution and mechanical stability during occupancy-driven operation. The results demonstrate symmetric and stable dynamic responses under alternating occupancy states, highlighting the relevance of mechanical modeling for the design and evaluation of occupancy-responsive ventilation systems.

Keywords: *Occupancy-driven ventilation, Ultrasonic sensing, Time-dependent mechanics, Rotational dynamics, Ventilation systems*

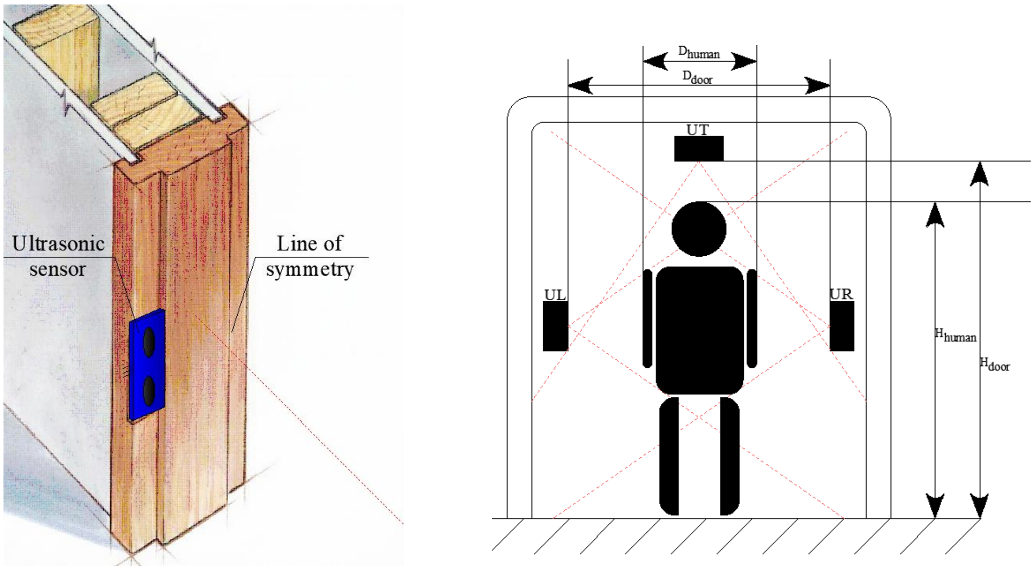
Introduction: Ventilation systems in buildings are increasingly required to operate under variable occupancy conditions, leading to frequent changes in operating regimes. However, many mechanically driven ventilation units are designed and analyzed assuming steady-state operation, while the transient mechanical effects associated with speed changes are often overlooked. Such effects may influence system stability, mechanical loading, and long-term performance.

Ultrasonic occupancy detection offers a practical and non-intrusive method for identifying changes in space usage at access points [1]. When applied to ventilation systems, occupancy-based operation introduces discrete transitions between predefined speed levels, resulting in time-dependent mechanical behavior of the rotating components [2,3]. Despite growing interest in occupancy-driven ventilation, the mechanical response of ventilation systems during these transitions has received limited attention.

This study examines the time-dependent mechanical behavior of an occupancy-regulated ventilation system using ultrasonic door-frame detection. A lumped-parameter rotational model is developed to analyze acceleration and deceleration processes induced by discrete operational state changes. Time-domain simulations are employed to characterize the dynamic response of the system under representative occupancy scenarios.

System description and operating principle: The investigated ventilation system represents a mechanically driven indoor air circulation unit whose operational regime varies according to the occupancy level of the conditioned space. The system comprises a ventilation fan coupled to an electric drive, a rotating shaft, and a structural housing integrated within the building envelope. From a mechanical standpoint, the ventilation unit operates as a rotational system subjected to time-varying loading conditions arising from changes in operational state [4,5]

The ultrasonic occupancy detection system employed in this study is implemented as a door-frame–mounted sensing arrangement, as illustrated in Figure 1. The ultrasonic transducers are embedded within the vertical door frame and positioned symmetrically with respect to the central axis of the opening. This configuration enables consistent detection geometry for occupants passing through the doorway, independent of lateral walking variations. By monitoring the sequence and timing of ultrasonic echoes during passage events, the system reliably identifies changes in occupancy level while remaining mechanically decoupled from the ventilation unit. The symmetric sensor placement ensures balanced sensing coverage and serves as a stable external input for triggering discrete operational state transitions of the ventilation system.



(a) (b)

Figure 1. Ultrasonic door-frame occupancy detection system: (a) detailed view of the door-frame segment illustrating sensor embedding and the line of symmetry; (b) front-view schematic of the door frame showing the symmetric placement of ultrasonic sensors.

Occupancy information is acquired using an ultrasonic door-frame detection system installed at the access points of the indoor environment. The proposed sensing arrangement consists of multiple ultrasonic transducers mounted on the door frame, enabling the detection of occupant passage direction and event timing as individuals enter or exit the space. This system provides discrete occupancy change signals rather than continuous flow measurements, thereby functioning independently of the mechanical airflow process.

The ultrasonic door system does not directly alter aerodynamic or thermal properties within the space. Instead, it serves as an external supervisory input that governs transitions between predefined operational states of the ventilation unit. Detected changes in occupancy level are translated into control commands that adjust the rotational speed of the fan to one of several discrete operating regimes.

Each operating regime corresponds to a specific mechanical loading condition applied to the electric drive and rotating components. An increase in occupancy initiates a transition to a higher operational state, resulting in elevated angular velocity and torque demand [6,7]. Conversely, a reduction in occupancy triggers a transition to a lower operational state, thereby decreasing mechanical loading. These transitions introduce inherently time-dependent behavior into the system, distinguishing it from conventional ventilation units operating at fixed steady-state conditions.

From a mechanical perspective, the dynamic response during acceleration and deceleration phases is governed primarily by the inertia of the rotating components and the resistive characteristics of the mechanical assembly. Since operational changes occur in a stepwise manner, the system repeatedly undergoes transient responses associated with torque variation and angular speed adjustment. Such behavior is representative of practical ventilation installations where discrete speed levels are commonly employed for reliability and control simplicity.

The described operating principle establishes a direct coupling between occupancy variation detected by the ultrasonic door system and the mechanical response of the ventilation unit. This coupling provides the foundation for the time-dependent mechanical modeling developed in the following section, where the transient rotational behavior of the system under occupancy-driven operation is analytically investigated.

Demand–based airflow requirement: The ventilation unit is idealized as a lumped-parameter rotational mechanical system composed of a fan, shaft, and electric drive. The rotating components are represented by an equivalent moment of inertia J, which governs the system's resistance to changes in angular velocity $\omega(t)$. Mechanical transmission elements are assumed rigid, and torsional deformation is neglected, allowing the system to be modeled using classical rotational dynamics.

Resistive mechanical effects, including bearing friction and fan-induced resistance, are represented by an equivalent load torque T_L. Occupancy-based regulation is assumed to induce stepwise changes in operating regimes, resulting in time-varying driving torque $T_D(t)$. Under these assumptions, the system behavior is governed by the rotational inertia relation

$$J\frac{d\omega(t)}{dt} = T_D(t) - T_L$$

which forms the basis for the time-dependent mechanical analysis developed in the following subsection.

Dynamic equation of rotational motion: The time-dependent mechanical behavior of the ventilation system is governed by the balance between the driving torque generated by the electric motor and the resisting load torque acting on the rotating assembly. Based on the lumped-parameter representation introduced in the previous subsection, the rotational motion of the system is described by the classical torque balance equation.

For a given occupancy state, the driving torque is assumed constant, yielding a first-order dynamic system with respect to angular velocity. Integrating the governing equation over time gives the transient response

$$\omega(t) = \omega_0 + \frac{T_D - T_L}{J}t$$

where ω_0 is the initial angular velocity at the beginning of the operating state. This relation describes the acceleration or deceleration of the ventilation system during transitions between occupancy-defined operating regimes and provides the foundation for analyzing time-dependent mechanical response under variable occupancy conditions.

Occupancy-driven operating states: Occupancy variation within the conditioned space is represented through a finite set of discrete operating states corresponding to low, medium, and high occupancy levels. Each occupancy state is associated with a predefined mechanical regime characterized by a target angular velocity and a constant driving torque. This stepwise representation reflects practical ventilation system operation and enables a clear mechanical interpretation of occupancy-induced regulation.

Accordingly, the driving torque is defined as a piecewise function of time,

$$T_D(t) = \begin{cases} T_L^{(1)}, & N \le N_1 \ (low\ occupancy) \\ T_L^{(2)}, & N_1 < N \le N_2 \ (medium\ occupancy) \\ T_L^{(3)}, & N > N_2 \ (high\ occupancy) \end{cases}$$

where N denotes the detected occupancy level and $N1$,$N2$ are predefined threshold values.

Each operating regime produces a distinct mechanical response governed by the dynamic equation of rotational motion, allowing time-dependent analysis of transitions between occupancy-defined mechanical states.

Transient response during state transitions: Transitions between occupancy-driven operating states induce transient mechanical responses characterized by acceleration or deceleration of the rotating assembly. When the driving torque exceeds the load torque, the system undergoes acceleration, whereas a reduction in driving torque results in deceleration. For each transition, the angular acceleration is given by

$$\alpha(t) = \frac{d\omega(t)}{dt} = \frac{T_D^{(i)} - T_L}{J}$$

where $T_D^{(i)}$ denotes the driving torque associated with the new occupancy state. The magnitude of angular acceleration is therefore directly governed by the torque difference and the system inertia.

Mechanical smoothness during state transitions is evaluated through the continuity of angular velocity and bounded acceleration levels. Sudden changes in torque can lead to high transient accelerations, which may affect mechanical stability and component longevity. To ensure smooth operation, transitions between occupancy states are assumed to satisfy

$$\omega(t^-) = \omega(t^+)$$

where t^- and t^+ denote instants immediately before and after a state change. This condition enables controlled mechanical transitions and forms the basis for assessing time-dependent system stability under repeated occupancy variations.

Analysis of mechanical response under occupancy variation: The developed time-dependent mechanical model is evaluated under practical occupancy variation scenarios derived from ultrasonic-based occupancy detection. The ultrasonic sensing system identifies changes in the number of occupants entering or leaving the space and generates discrete occupancy signals that trigger transitions between predefined operating regimes of the ventilation system. These signals are treated as step inputs to the mechanical model, directly influencing the applied driving torque. The resulting dynamic response is simulated in MATLAB by numerically integrating the governing rotational equation.

Figure 2 illustrates the time-dependent angular velocity response of the ventilation system under alternating occupancy conditions detected by the ultrasonic sensing framework. At the instants corresponding to transitions from low to high occupancy, the control system increases the applied driving torque to the appropriate operating level. As shown in the figure, the angular velocity responds with a smooth transient rise governed by the rotor inertia and viscous damping, followed by a steady-state regime once the nominal operating speed is attained. The nearly linear slope observed during the transient phase reflects the dominance of inertial effects, confirming the suitability of the lumped-parameter rotational model for practical ventilation dynamics.

Subsequent transitions from high to low occupancy are also depicted in the same figure. In these intervals, ultrasonic detection of occupant departure initiates a reduction in the driving torque, resulting in a deceleration process characterized by negative angular acceleration. The angular velocity decreases smoothly toward the lower operating level without oscillatory behaviour, indicating mechanically stable operation. The comparable magnitudes of acceleration and deceleration slopes demonstrate symmetric dynamic behaviour during state transitions, consistent with the torque balance formulation presented in Section 3 and representative of realistic ventilation system control.

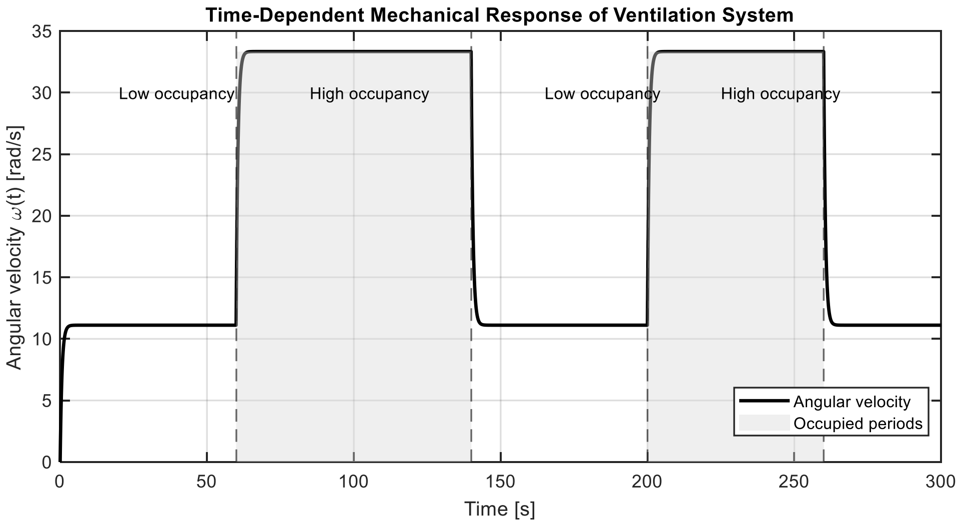


Figure 2. Time-dependent angular velocity response of the ventilation rotor under alternating low and high occupancy conditions, highlighting acceleration and deceleration phases.

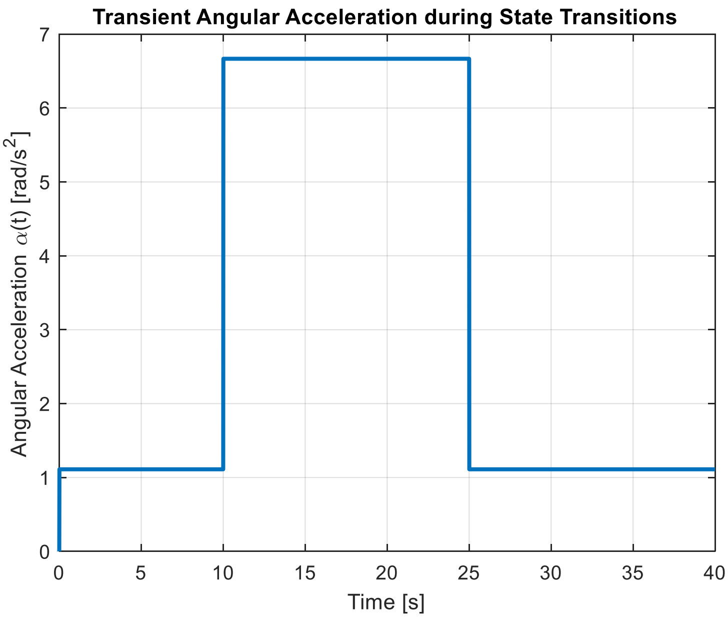


Figure 3. Transient angular acceleration of the ventilation system under occupancy-driven operational state changes.

The time history of angular acceleration obtained from MATLAB simulation is shown in Figure 3. Peak acceleration values occur at the moments of operating state transitions, while steady occupancy periods correspond to near-zero acceleration. These results highlight the mechanical significance of occupancy-driven regulation: frequent changes in detected occupancy lead to repeated transient mechanical loading. However, when transitions are implemented in a stepwise but bounded manner, the resulting acceleration levels remain within mechanically acceptable limits, ensuring stable system operation.

The continuity of angular velocity observed across all simulated transitions confirms mechanically smooth behavior of the ventilation system under ultrasonic-based occupancy regulation. No impulsive responses or discontinuities are present in the simulated results, indicating that the proposed regulation strategy does not introduce mechanically adverse effects. These findings demonstrate that practical occupancy variation, as detected by ultrasonic sensing at room access points, can be effectively incorporated into ventilation operation without compromising mechanical stability.

Overall, the MATLAB-based analysis confirms that occupancy-responsive ventilation systems exhibit predictable and controllable mechanical behavior when modeled using time-dependent rotational dynamics. The integration of ultrasonic occupancy detection provides a practical mechanism for initiating operational changes, while the mechanical response remains governed by fundamental inertia and torque relationships. This validates the applicability of the proposed model for practical building ventilation systems operating under dynamic occupancy conditions.

Conclusion: This study examined the time-dependent mechanical behavior of an occupancy-regulated ventilation system operating under discrete operational state transitions. By incorporating ultrasonic door-frame detection as an external occupancy input, variations in space usage were directly linked to changes in mechanical loading of the ventilation unit. A lumped-parameter rotational model was developed to capture the transient response of the system during acceleration and deceleration phases. The results demonstrate that inertia and resistive effects govern the angular velocity evolution, producing smooth and symmetric dynamic behavior under alternating occupancy conditions.

The findings highlight the importance of considering transient mechanical effects in the analysis and design of ventilation systems subjected to variable operation. Stepwise occupancy-driven regulation, representative of practical building installations, introduces repeated dynamic responses that cannot be adequately described by steady-state assumptions alone. The presented modeling framework provides a practical basis for evaluating mechanical stability and performance in occupancy-responsive ventilation systems and may be extended in future work to include more complex loading conditions and coupled airflow effects.

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