Dynamics and Active Vibration Suppression of an Aerial Rescue Ladder

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Abstract

Your abstract.

1 Introduction

1.1 Problem Statement

In the field of construction and rescue operations, an aerial ladder is commonly used to transport personnel from the ground to elevated working positions. However, when operating at height, environmental factors such as wind gusts, ground vibrations, and sudden external disturbances can induce structural vibrations in the ladder system, posing significant safety risks to both operators and equipment. Thus it is necessary to understand the behavior of such aerial ladders under operation using simulation, and come up with a solution to mitigate the effects of environmental factors.

Figure 1: Aerial Ladder of Fire Truck

1.2 Aims and Objectives

This project aims to investigate the effectiveness of an active damping system in mitigating the vibrations of an aerial ladder subjected to external dynamic loads that simulate real-world environmental conditions. The study will focus on the ladder's structural response, stability, and safety performance, providing insight into how active control mechanisms can enhance reliability during high-altitude operations.

To solve this problem, we have following objectives,

- **Develop a simplified dynamic model of the aerial ladder structure.** Establish a mathematical representation of the ladder using beam theory, treating it as a flexible multi-segment Euler–Bernoulli beam with distributed mass and a concentrated end mass to capture both structural flexibility and payload effects.
- **Analyze the vibration and deformation response.** Use a discrete spring–mass model with implicit Euler time integration to evaluate tip deflection and oscillation behavior under varying external loads.
- **Design and evaluate an active damping control strategy.** Apply the active oscillation damping concept proposed by Kharitonov et al. (2007) using feedback signals from strain or angular velocity sensors to suppress the dominant vibration modes [1].
- **Compare controlled and uncontrolled cases.** Assess the effectiveness of the proposed damping system by comparing structural responses, stability margins, and residual vibrations between passive and actively controlled configurations.
- **Interpret results to guide future ladder design.** Provide practical insights into how active damping can enhance operational safety and inform future design or retrofitting of rescue ladder systems.

2 Literature Review

2.1 Background and Research Motivation

Upon reviewing modern aerial ladder systems used in firefighting applications, it was found that ladders lacking active damping mechanisms can experience significant instability when exposed to environmental disturbances such as wind gusts—particularly when extended to their maximum operating length. According to Horváth et al. (2020), *"pressure created by sudden wind gusts can swing the ladder structure by up to one meter, which poses a serious operational risk, especially under maximum load conditions."* [2] These findings highlight the critical need for vibration mitigation and stability enhancement measures in aerial ladder design to ensure safe and reliable operation during adverse environmental conditions.

2.2 Modeling Approaches in Ladder Dynamics

In their study on semi-active vibration control of offshore jacket platforms, Lavassani et al. (2025) demonstrated that integrating a semi-active tuned mass damper inerter (SATMDI) with a feedback-based control strategy can substantially improve the structural performance under dynamic environmental loads such as wind and waves [3]. The authors highlighted that a real-time feedback control system—which continuously monitors the displacement and velocity responses of the structure—can dynamically regulate the damping force through an adaptive actuator, such as a magnetorheological (MR) damper. By adjusting the damper's voltage input according to the measured vibration state, the system effectively tunes its energy-dissipation capacity to the instantaneous loading condition. This inspired us to come up with a feedback system that actively monitors the displacement and orientation of the aerial ladder, then adjusts the damping coefficient accordingly to reduce its vibration.

In addition, the work of Kharitonov et al. (2007) provides valuable insights into the active control of ladder oscillations. In their study, the fire-rescue turntable ladder was modeled as a hybrid system that combines an Euler–Bernoulli beam (distributed parameter system) with a concentrated end mass representing the rescue cage. By deriving analytical eigenfunctions and constructing a modal representation of the system, the authors designed a feedback controller that relies only on strain gauge and gyroscope measurements. This approach successfully damped both the fundamental and the first overtone vibration modes, achieving stable operation even for ladders longer than 30 m and requiring only limited microcontroller resources [1]. The study demonstrates that a low-order feedback system based on a few dominant modes can effectively stabilize large flexible structures. This idea directly inspires the present project to investigate a simplified active damping strategy that uses limited sensor feedback to suppress ladder oscillations under dynamic loading conditions.

Beyond these studies, earlier work by Aschemann et al. (2002) proposed a trajectory control method for fire-rescue turntable ladders based on a multibody dynamic model and a decentralized feedback approach [4]. Their controller effectively reduced the primary oscillation mode but was unable to sufficiently suppress higher-order vibrations at extended ladder lengths. Zuyev and Sawodny (2005) later introduced a stabilization strategy for flexible manipulators with passive joints, employing Galerkin approximation to derive the feedback law [5]. However, the method required high computational power and was not suitable for real-time microcontroller implementation. These limitations highlight the need for simplified, low-computation active damping approaches that can stabilize large flexible structures while remaining feasible for real-time control.

2.3 Identified Gaps and Proposed Focus

Although existing research has explored both passive and active vibration control methods, most approaches either require complex modal computations or depend on high-performance hardware for real-time implementation. As a result, there remains a clear need for a simplified yet effective active damping strategy that can operate with limited sensing and computational resources.

Given the highly dynamic and disturbance-sensitive nature of the aerial ladder, an open-loop control configuration would be inadequate, as it cannot automatically compensate for unpredictable disturbances. Instead, a closed-loop feedback control system is more appropriate for this application, since it allows continuous adjustment of the control input based on the measured system response.

As Frank (2018) notes in *Control Theory Tutorial*, *"closed-loop feedback control allows a system to correct for incomplete knowledge of intrinsic system dynamics and for unpredictable perturbations acting on the system."* [6] Building on this principle, the present project aims to integrate a feedback-based active damping law—conceptually inspired by Kharitonov et al. (2007)—into a discrete spring–mass simulation model. This combination provides a practical framework for real-time oscillation suppression while preserving computational efficiency.

3 Methodology

3.1 Implementation Overview

To mitigate vibrations induced by environmental factors (such as wind gusts), a closed-loop feedback control system will be designed. This system continuously monitors the displacement of the aerial ladder using position or acceleration sensors. The sensor output produces a signal proportional to the absolute displacement of the ladder. This signal is then transmitted to an active damper unit mounted at the base of the ladder.

3.2 Geometric Modeling of the Ladder

The aerial ladder is modeled as a slender flexible beam of total length

$$L = 20 \text{ m},$$

initially oriented at

$$\theta_0 = 60^\circ$$

with respect to the horizontal. The beam is discretized into

$$N = 51$$

nodes, giving 50 uniform segments of spacing

$$\Delta L = \frac{L}{N-1} = 0.4 \text{ m}.$$

Each node carries two translational degrees of freedom,

$$q = [x_0, y_0, x_1, y_1, \ldots, x_{N-1}, y_{N-1}]^T,$$

resulting in a total of $2N = 102$ DOFs. The first two nodes are clamped, representing the rigid attachment of the ladder base to the turntable of the fire truck.

3.3 Cross-Section and Material Properties

The ladder is treated as a hollow circular aluminum tube of outer radius

$$r_o = 0.10 \text{ m}, \qquad r_i = 0.09 \text{ m},$$

corresponding to a diameter of 20 cm and a 1 cm wall thickness. The Young's modulus is set to

$$Y = 70 \text{ GPa},$$

typical for aluminum alloy structures.

The axial and bending rigidities are therefore

$$EA = Y\,\pi(r_o^2 - r_i^2), \qquad EI = Y\frac{\pi}{4}(r_o^4 - r_i^4).$$

A lumped mass model is used, where each node is assigned a spherical mass of radius

$$R = \frac{\Delta L}{10} = 0.04 \text{ m},$$

and density

$$\rho = 2700 \text{ kg/m}^3.$$

This yields a nodal mass

$$m_k = \frac{4}{3}\pi R^3 \rho.$$

To emulate the effect of onboard equipment or a firefighter load, the mid-span node is assigned a larger radius $R = 0.025$ m.

3.4 Discrete Elastic Energy Formulation

The elastic behavior of the ladder is obtained from stretching and bending energies. For each segment, the stretching energy is

$$E_s = \frac{EA}{2}\left(\frac{\ell_k - \Delta L}{\Delta L}\right)^2, \qquad \ell_k = \|\mathbf{x}_{k+1} - \mathbf{x}_k\|.$$

For each triplet of nodes $(k-1, k, k+1)$, the discrete curvature

$$\kappa_k = \left[2\frac{\mathbf{t}_{k-1} \times \mathbf{t}_k}{1 + \mathbf{t}_{k-1} \cdot \mathbf{t}_k}\right]_z$$

is used to construct the bending energy

$$E_b = \frac{EI}{2}(\kappa_k - \kappa_0)^2, \quad \kappa_0 = 0.$$

Elastic forces and stiffness matrices are obtained from the energy gradients:

$$F_s = -\nabla E_s, \qquad F_b = -\nabla E_b,$$
$$K_s = \nabla^2 E_s, \qquad K_b = \nabla^2 E_b.$$

3.5 Dynamic Model

The full equation of motion is

$$M\ddot{q} + C\dot{q} + F_{\text{elastic}}(q) = W_{\text{ext}}(t),$$

where

- M is the diagonal lumped mass matrix,
- $C = \alpha_M M$ is Rayleigh mass-proportional damping with $\alpha_M = 0.002$,
- $F_{\text{elastic}} = F_s + F_b$,
- W_{ext} includes gravity, the base torsional actuator, and tip wind loading.

Time integration is performed using the fully implicit Euler scheme,

$$q_{n+1} = q_n + dt\, u_{n+1}, \qquad u_{n+1} = u_n + dt\, \dot{u}_{n+1},$$

and the nonlinear residual equation

$$f(q_{n+1}) = 0$$

is solved via Newton–Raphson iteration using the assembled global Jacobian.

3.6 Semi-Active Base Damping Control

A torsional spring–damper is placed between nodes 1 and 2 to represent the powered turntable joint. The resulting moment is

$$M = -k_\theta(\phi - \phi_0) - c_\theta(t)\,\dot{\phi},$$

where ϕ and $\dot{\phi}$ are the base rotation angle and angular velocity, and $k_\theta = 3000$ N m/rad.

The damping coefficient is modulated semi-actively according to

$$s = \phi\,\dot{\phi},$$

$$c_\theta(t) = \begin{cases} c_{\max}, & s > 0 \\ c_{\min}, & s < 0 \\ c_{\text{base}}, & s = 0, \end{cases}$$

with smoothing applied to avoid numerical discontinuities. This strategy dissipates energy when the system moves toward equilibrium, and reduces damping when it moves away, following established semi-active vibration suppression principles.

3.7 External Tip Loading

To simulate a transient wind gust acting on the ladder basket, a horizontal sinusoidal force is applied at the tip node:

$$F_x(t) = 500\sin(\omega t), \qquad \omega = \frac{2\pi}{8\text{ s}}.$$

The load is applied only during the first

$$0 \le t \le 4\text{ s},$$

after which the ladder undergoes free vibration. This excitation profile follows typical gust-loading patterns used in ladder oscillation studies.

4 Results and Discussions

References

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