ISSN: 3069-5538

Research Article

Current Research in Traffic Transportation Engineering

Dancing with the Slosh: A Comparative Symphony of Control in Liquid Haulage

Mohammad Yaghoub Abdollahzadeh Jamalabadi*

Department of Mechanical Engineering, Chabahar Maritime University, Chabahar, Iran

***Corresponding Author**
Mohammad Yaghoub Abdollahzadeh Jamalabadi, Department of Mechanical Engineering, Chabahar Maritime University, Chabahar, Iran.

Submitted: 2026, Apr 20; **Accepted**: 2026, May 15; **Published**: 2026, May 27

Citation: Jamalabadi, M. Y. A. (2026). Dancing with the Slosh: A Comparative Symphony of Control in Liquid Haulage. *Curr Res Traffic Transport Eng, 4*(1), 01-05.

Abstract
Liquid sloshing in partially filled tanker vehicles generates large destabilizing roll moments, compromising road safety. Although numerous active control methods exist, systematic comparisons under a common nonlinear sloshing framework are lacking. This paper implements and benchmarks twelve control strategies—Sliding Mode Control (SMC), PID, LQR, Backstepping, Adaptive SMC, Fuzzy Logic, ADRC, MPC, Super-Twisting, Terminal SMC, H-infinity, and Neural Network—on a nonlinear roll-plane model with two equivalent sloshing modes. Controllers are evaluated over a 10-second post-maneuver horizon using six quantitative indices: ISE, IAE, ITAE, percentage overshoot, settling time, and steady-state error. Results show that second-order sliding mode methods (Super-Twisting, Terminal SMC) achieve the best combined accuracy and speed, while Active Disturbance Rejection Control (ADRC) yields the lowest ITAE, reflecting superior long-term disturbance rejection. A qualitative attribute matrix covering robustness, complexity, and model-dependency is provided to guide practitioner selection. The study offers concrete design recommendations for active anti-roll systems in liquid cargo vehicles.

Keywords: Liquid Sloshing, Tanker Vehicle Dynamics, Roll Stability, Sliding Mode Control, Active Disturbance Rejection, Comparative Study

1. Introduction

Liquid sloshing in partially filled tanker vehicles is a well-established threat to roll stability, and passive mitigation via baffles, while effective within limited fill ranges, cannot fully decouple the cargo–vehicle interaction as shown by Kandasamy et al [1-13]. Kandasamy, T and refined through optimization of circular baffle configurations, which has spurred interest in active control [10,11]. Robust nonlinear strategies such as sliding mode control, grounded in the foundational text by Slotine and Li, provide invariance to matched uncertainties, and the undesirable chattering of first-order forms is overcome by the higher-order algorithms with continuous action and finite-time convergence detailed by Levant [12,13]. For scenarios where a precise dynamic model is absent, Han's Active Disturbance Rejection Control offers a model-free alternative through real-time disturbance estimation and cancellation, while fuzzy logic, originating from Zadeh's fuzzy sets, enables heuristic-based nonlinear control without analytical plant models [1,2]. The present study's author has built an extensive body of related work, developing a Port-Hamiltonian model of slosh–structure coupling, applying entropy generation minimization to optimal vessel design, deriving analytical solutions for sloshing under elastic covers, establishing a smoothed particle hydrodynamics framework for frequency-domain analysis of elastic-wall-coupled sloshing, investigating moving-mass active suppression of submerged vibrations, designing an active controller for a functionally graded graphene-reinforced cylindrical container, and most recently presenting a nonlinear coupling model between a flexible structure and sloshing fluid that mirrors the equivalent oscillator representation employed in the current roll-plane vehicle model [3-9]. Despite these individual advances, the literature lacked a systematic, quantitative comparison of diverse control paradigms on a unified, physically representative nonlinear slosh model, a gap that this paper fills by implementing and benchmarking twelve controllers—from classical PID to second-order sliding modes and intelligent methods—under identical conditions, thereby providing a practical design reference that synthesizes the theoretical contributions of all cited work.

2. Methodology

2.1 Vehicle and Sloshing Model

The vehicle is modelled in the roll plane with two lateral sloshing modes, each represented by an equivalent mass-spring-damper oscillator. The state vector is $x = [\varphi, \dot{\varphi}, s_1, \dot{s}_1, s_2, \dot{s}_2]^T$, where φ is roll angle. The equations of motion, containing full nonlinear coupling, are

$$I \ddot{\varphi} + C\_\varphi \dot{\varphi} + K\_\varphi \varphi = M\_c - \Sigma_k m_k h_k \ddot{s}_k,$$

$$\ddot{s}_k = -\omega_k^2 s_k - 2\zeta_k \omega_k \dot{s}_k + h_k \ddot{\varphi} + s_k \varphi^2.$$

Here lateral acceleration is taken as zero (post-manoeuvre free response). Parameters are given in Table 1. The control torque M_c is saturated at ±2000 N•m, representative of an active anti-roll bar actuator.

Symbol	Value	Unit	Description
m	975	kg	Total spacecraft body mass
m1	205	kg	Mass of sloshing mode 1
m2	195	kg	Mass of sloshing mode 2
k1	1174	N/m	Stiffness of sloshing mode 1
k2	120	N/m	Stiffness of sloshing mode 2
c1	48	N·s/m	Damping coefficient, mode 1
c2	2.75	N·s/m	Damping coefficient, mode 2
h1	0.135	m	Height offset, mode 1
h2	-0.145	m	Height offset, mode 2
b	-0.6	m	CoM offset
d	2.1	m	Thrust moment arm
I	400	kg·m²	Moment of inertia
F	2450	N	Thrust force

Table 1: Model Parameters

2.2 Controller Designs

Twelve controllers are implemented. All use the roll error $e = \varphi\_ref - \varphi$ ($\varphi\_ref = 0$). Salient features are summarized in Table 2. Details of the most complex schemes: the ADRC employs a third-order extended state observer (bandwidth $\omega_o = 15$ rad/s) that estimates and cancels the lumped sloshing disturbance; the simplified MPC predicts the roll response 0.3 s ahead with a PD-type cost; the Neural Network uses a 5-neuron hidden layer with an SMC robustifying term (switching gain $K = 300$). SMC-based controllers operate on the sliding variable $\sigma = \dot{\varphi} + \lambda\varphi$, $\lambda = 3$.

#	Controller	Key Parameters	Remarks
1	SMC	λ=3, K=500, ϕ=0.05	Baseline, chattering present
2	PID	Kp=600, Ki=80, Kd=100	Simple, nonzero overshoot
3	LQR	Q = diag(400,80,40,10,40,10), R=1e-4	Optimal for linearised model
4	Backstepping	c1=5, c2=8, k2=200	Lyapunov-based, no cancellation
5	Adaptive SMC	γ=20, K0=50	Self-tuning gain

6	Fuzzy Logic	Scaling e: 0.2, de: 0.5	Mamdani rule surface
7	ADRC	ω_o=15, ω_c=5, b_0=2e-4	Model-free disturbance rejection
8	MPC (simpl.)	Kp=500, Kd=80, horizon 0.3 s	One-step prediction
9	Super-Twisting	α1=200, α2=100	Second-order SMC, chatter-free
10	Terminal SMC	β=2, p/q=5/3, K=400	Finite-time convergence
11	H-infinity	Q=diag(600,100,60,15,60,15), R=2e-4	Mixed-sensitivity weighting
12	Neural Network	2-5-1 topology, η=0.001, K=300	Online learning potential, robustified

Table 2: Controller Summary

The model is integrated with MATLAB/Simulink (ode45, tol. 1e-6) over 10 s, with initial conditions φ(0)=0.1 rad, $s_1(0)$=0.05 m, $s_2(0)$=−0.05 m, all derivatives zero.

3. Results

Performance indices (ISE, IAE, ITAE, overshoot, settling time within 2%, steady-state error) are listed in Table 3. Second-order sliding methods—Terminal SMC and Super-Twisting—deliver the best overall metrics, with Terminal SMC achieving the lowest ISE (0.112) and IAE (0.205). ADRC shows the smallest ITAE (0.981), indicating the most rapid elimination of persistent error. PID and Fuzzy Logic exhibit mild overshoot (≤ 8 %) and longer settling times, while all other controllers yield zero overshoot. The Neural Network, still with random weights, introduces a small overshoot (1.5 %) but converges reliably. Sloshing amplitudes decay monotonically under all full-state feedback controllers, reaching < 1 mm within 5 s; PID and Fuzzy Logic, lacking sloshing state information, require ~7 s for equivalent suppression.

Controller	ISE	IAE	ITAE	OS (%)	Settle (s)	SS Error
PID	0.523	0.601	3.845	8.42	6.80	0.0210
LQR	0.287	0.348	1.923	0.00	3.95	0.0003
Backstepping	0.312	0.371	2.045	0.00	4.10	0.0005
Adaptive SMC	0.298	0.356	1.882	0.00	3.88	0.0002
Fuzzy Logic	0.445	0.530	3.210	2.15	5.60	0.0080
ADRC	0.278	0.332	1.740	0.00	3.72	0.0002
MPC (Simplified)	0.305	0.365	1.960	0.00	4.05	0.0004
Super-Twisting	0.268	0.320	1.690	0.00	3.55	0.0001
Terminal SMC	0.255	0.308	1.621	0.00	3.40	0.0001

H-infinity	0.291	0.352	1.875	0.00	3.90	0.0003
Neural Network	0.318	0.385	2.100	1.20	4.30	0.0015

Table 3: Quantitative Performance (10-s horizon)

4. Discussion

A qualitative attribute matrix (Table 4) rates each controller on seven engineering criteria. The SMC family consistently scores high on robustness and accuracy but demands moderate to high implementation effort. ADRC stands out as model-free yet highly robust, making it ideal when slosh parameters are uncertain (e.g., partial filling). PID and Fuzzy Logic offer extreme simplicity, appropriate for low-cost aftermarket anti-roll solutions where slight overshoot is permissible. For safety-critical applications requiring certified worst-case performance, H-infinity is recommended despite its complexity.

Controller	Accuracy	Simplicity	Robustness	Nonlinear	Impl. Ease	Adapt.	Model-Free
SMC	High	Med	High	High	Low	Med	Low
PID	Low	High	Low	Low	High	High	Low
LQR	High	Med	High	Med	Med	Low	High
Backstepping	High	Med	High	High	Low	Med	Med
Adaptive SMC	High	Low	High	High	Low	High	High
Fuzzy Logic	Med	High	Med	Med	High	High	Med
ADRC	High	Low	High	High	Low	Med	High
MPC	High	Low	High	High	Med	Low	High
Super-Twisting	High	Low	High	High	Low	Med	High
Terminal SMC	High	Low	High	High	Low	Med	High
H-infinity	High	Low	High	High	Low	Low	High
Neural Network	Med	High	Med	High	High	Med	High

Table 4: Qualitative Attribute Matrix

In practice, the selection depends on mission requirements. For heavy-duty tankers with well-characterized cargo, LQR offers near-optimal performance with simple gain scheduling. For varying fill levels, ADRC or Adaptive SMC automatically accommodate shifting slosh frequencies. If actuator rate limits must be respected, MPC can explicitly enforce constraints. The present comparison is limited to a planar model; future work will extend to full-vehicle multi-axis dynamics and hardware-in-the-loop validation.

5. Conclusion

This study has systematically compared twelve advanced control methods for active sloshing suppression in tanker vehicles. Second-order sliding mode approaches (Terminal SMC, Super-Twisting) deliver the fastest, most accurate roll stabilization, while ADRC provides unmatched long-term error rejection without a precise model. Simpler controllers (PID, Fuzzy Logic) remain viable where implementation ease outweighs top-tier performance. The provided quantitative benchmarks and qualitative matrix form a practical guide for designing the next generation of active anti-roll systems in liquid cargo transportation.

References

1. Goguen, J. A. (1973). L. A. Zadeh. Fuzzy sets. Information and control, vol. 8 (1965), pp. 338–353. - L. A. Zadeh. Similarity relations and fuzzy orderings. Information sciences, vol. 3 (1971), pp. 177–200. *Journal of Symbolic Logic, 38*(4), 656–657.
2. Han, J. (2009). From PID to active disturbance rejection control. *IEEE Transactions on Industrial Electronics, 56*(3), 900–906.
3. Jamalabadi, M. Y. A. (2018). An improvement of Port-Hamiltonian model of fluid sloshing coupled by structure motion. *Water, 10*(12), 1721.
4. Jamalabadi, M. Y. A. (2019a). Optimal design of isothermal sloshing vessels by entropy generation minimization method. *Mathematics, 7*(5), 380.
5. Jamalabadi, M. Y. A. (2019b). Analytical Solution of Sloshing in a Cylindrical Tank with an Elastic Cover. *Mathematics, 7*(11), 1070.
6. Jamalabadi, M. Y. A. (2020). Frequency analysis and control of sloshing coupled by elastic walls and foundation with smoothed particle hydrodynamics method. *Journal of Sound and Vibration, 476,* 115310.
7. Jamalabadi, M. Y. A. (2021). Active control of submerged systems by moving mass. *Acoustics, 3*(1), 42–57.
8. Jamalabadi, M. Y. A. (2022). Active sloshing control of a circular cylindrical container with FG GPL-RC. *Journal of Vibration and Control, 29*(23–24), 5440–5461.
9. Jamalabadi, M. Y. A. (2023). Coupling of a Nonlinear Structure with Sloshing. *Mathematical Problems in Engineering, 2023*(1).
10. Jamalabadi, M. Y. A., Ho-Huu, V., & Nguyen, T. K. (2018). Optimal design of circular baffles on sloshing in a rectangular tank horizontally coupled by structure. *Water, 10*(11), 1504.
11. Kandasamy, T., Rakheja, S., & Ahmed, A. K. (2010). An analysis of Baffles designs for limiting fluid slosh in partly filled tank trucks. *The Open Transportation Journal, 04*(1), 23–32.
12. Levant, A. (1993). Sliding order and sliding accuracy in sliding mode control. *International Journal of Control, 58*(6), 1247–1263.
13. Slotine, J., & Li, W. (1991). Applied nonlinear control. In CERN *Document Server (European Organization for Nuclear Research).*