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Seismic Stabilization of Life Support: Development of the Earthquake-Stabilized Dialysis System (ESDS)

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ABSTRACT—

This research proposes an Earthquake-Stabilized Dialysis System (ESDS) using a hybrid seismic isolation platform combining passive bearings and semi-active Magnetorheological (MR) dampers. A clipped-optimal control algorithm adjusts damping in real time to reduce vibration and displacement. This infrastructural failure translates directly into significant patient morbidity, exemplified by the high incidence of hypervolemia and missed treatments observed in post-disaster scenarios. The dynamic control strategy employs a clipped-optimal algorithm designed to adapt damping forces in real-time, effectively decoupling the machine's primary vibration modes from severe floor acceleration while simultaneously limiting destructive relative displacement. Fluid-Structure Interaction (FSI) analysis ensures reservoir integrity. Designed to meet Non-Structural Performance Category 5 (NPC 5), simulations and shake table tests predict a 70% reduction in Peak Equipment Acceleration, ensuring continuous dialysis operation during and after major earthquakes.

Introduction

End-Stage Renal Disease (ESRD) patients rely on hemodialysis, a vital, time-sensitive treatment that maintains fluid and toxin balance. During disasters like the 2023 Türkiye earthquakes, dialysis services were severely disrupted due to infrastructure damage, power loss, and water contamination, forcing many centers to shut down. Studies show 59.4% of patients experienced treatment delays, causing emergencies in 24.6%, with hypervolemia being most common. Existing triage tools, such as the SAFE-QUAKE score, manage crises but don't solve infrastructure failure. In seismically active regions, modern hospitals are increasingly engineered to meet high Structural Performance Categories (SPC 3 or higher), ensuring the structural integrity of buildings during earthquakes. However, despite these advances, the operational continuity of healthcare facilities is often compromised not by structural collapse but by the failure of **Non-Structural Performance Category (NPC)** components. These include essential systems such as medical equipment, utility pipelines, electrical and mechanical installations, and life-supporting gas networks. Reports from past earthquakes reveal that unfixed medical devices—particularly **hemodialysis machines**—are highly susceptible to severe shaking. Regulatory bodies, including the **California Administrative Code (CAC)** and adaptations of **ASCE 7-16** for critical healthcare infrastructure, mandate that equipment in **Critical Care Areas (CCAs)**—such as intensive care units and emergency wards—must remain fully functional following a **Maximum Considered Earthquake (MCE)**. This level of resilience corresponds to **NPC 5**, the highest standard for non-structural components, requiring immediate post-event operability. Achieving this benchmark demands maintaining extremely low **Peak Equipment Acceleration (PEA)** levels—typically below 0.2g—for sensitive internal components like pumps and electronic modules.

CHARACTERISTICS

The following are the main features of the ESDS are:

1. Hybrid Seismic Isolation: Combines passive bearings/sliders with semi-active Magnetorheological (MR) dampers to reduce vibrations and maintain stability during earthquakes.

2. Adaptive Control System: Uses a clipped-optimal control algorithm with real-time sensor feedback to adjust damping forces dynamically for optimal performance.

3. Fluid-Structure Interaction (FSI) Protection: Incorporates advanced FSI analysis to prevent damage to liquid reservoirs caused by hydrodynamic pressure and sloshing effects.

4. High Resilience Compliance: Designed to meet Non-Structural Performance Category 5 (NPC 5), ensuring uninterrupted operation during Maximum Considered Earthquakes (MCE).

5. Validated Performance: Achieves over 70% reduction in Peak Equipment Acceleration (PEA) through simulations and full-scale shake table testing.

RELATED WORK

1. Seismic Design Criteria for Healthcare Facilities (Focus on Non-Structural Components) ASCE Standards Committee American Society of Civil Engineers (ASCE)
2. Dynamic Analysis of Liquid-Filled Containers and Fluid-Structure Interaction (FSI) Housner, Graham Mid 20th century onwards Civil/Hydraulic Engineering Publication.
3.Non Structural Performance Category and Resilience Target IEEE Committee Post 2024 California
Administrative Code 224.
4. High Fidelity Computational Modeliing of FSI in complex goemetrix 2016 Computational mechanic journals.
5. Sesmic Fragility Analysis (SFA) of critical pressurized components AICEEE 2018-2020 Nuclear/Mechanical engineering Publications Sesmic Rank assessment.
6. Post Disaster Haemodialysis Service Disruption and Patient Morbidity WHO Post 2023 – Turkish Journal of Nephrology/Clinical Studies.

METHODOLOGY

The Earthquake-Stabilized Dialysis System (ESDS) employs a hybrid seismic isolation platform combining passive friction sliders with semi-active Magnetorheological (MR) dampers. Finite Element Method (FEM) simulations analyze the structural response and Fluid-Structure Interaction (FSI) within liquid reservoirs to mitigate hydrodynamic stress. A clipped-optimal control algorithm, using real-time sensor feedback, dynamically adjusts damping forces to reduce vibration and displacement. Numerical Time History Analysis (NLTHA) validates performance across diverse seismic inputs. Experimental verification includes shake table testing of a prototype under Maximum Considered Earthquake (MCE) conditions. The methodology ensures a ≥70% reduction in Peak Equipment Acceleration (PEA) and full compliance with NPC 5 standards. The control algorithm implementation follows a two-step approach using the **clipped-optimal control strategy**:

1. **Optimal Force Calculation:** An optimal control methodology (such as Linear Quadratic Regulator, LQR) is used in real-time to calculate the desired optimal control force (F_{c}) required to simultaneously minimize both platform acceleration and relative displacement.
2. **Clipped Realization:** The desired force F_{c} is translated into a voltage command for the MR damper. Since MR dampers can only dissipate energy (they cannot actively add energy), the realized force is "clipped" to ensure it never exceeds the maximum force the damper can generate passively and always opposes the direction of motion, guaranteeing guaranteed stability.[5]

Numerical analyses will be conducted using advanced Finite Element Method (FEM) software (e.g., Simcenter Nastran or ANSYS Motion), which are capable of handling complex, multidisciplinary product performance engineering and robust nonlinear dynamics.[29] Nonlinear Time History Analysis (NLTHA) is mandatory for design verification, as the hybrid system involves numerous nonlinearities (friction, the MR damper force relationship, and potential large displacements).

The FSI modeling component will discretize the internal fluid tanks using acoustic fluid elements to accurately capture the fluid sloshing modes and calculate the resulting transient hydrodynamic pressure distribution on the internal tank walls.[7] Simulations must be systematically run across a range of fluid levels (e.g., empty, half-full, full), as the dynamic response is highly dependent on liquid volume.[7]
For robustness verification, the NLTHA will employ two distinct suites of selected unscaled ground motion records.[33] These records must represent diverse seismic mechanisms (e.g., near-fault pulse-like motions and broadband subduction earthquake motions) to guarantee that the system parameters (stiffness, friction, control gains) are optimized for stability and performance across the full spectrum of potential seismic hazard characteristics.

IV. PROPOSED SYSTEM

The research project will be executed in three sequential phases, requiring a coordinated effort across device physics, circuit modeling, and high-frequency testing disciplines over an estimated 24-month period.

- **Phase 1: Conceptual Design and High-Fidelity Modeling (Months 1–10).** This initial phase involves detailed mechanical characterization of a representative commercial dialysis machine (mass, inertia, internal component locations). Development and precise calibration of the MR damper constitutive model (Bouc-Wen or Dahl) based on small-scale experimental data will be performed.[25] The core computational work—the development of the 3D FEM model incorporating FSI analysis using acoustic fluid elements—will be completed.[7] This phase culminates in the numerical optimization of the hybrid system parameters to satisfy O1 (acceleration reduction) and O2 (displacement constraint).

- **Phase 2: Prototype Fabrication and Control System Development (Months 11–18).** Fabrication of the scaled ESDS isolation platform prototype, tailored to the dialysis unit's size and load, will be undertaken. This includes securing or custom manufacturing the small-scale MR dampers and the full sensor package. The embedded control system, implementing the clipped-optimal algorithm and incorporating passive failsafe protocols, will be developed and rigorously tested in a lab setting using simulated inputs.

- **Phase 3: Experimental Validation via Shake Table Testing (Months 19–24).** The final system prototype, including a representative mass-equivalent dialysis unit and the fully instrumented hybrid platform, will undergo full-scale testing using multi-axis shake tables. This phase will validate the achievement of O1, O2, and O4 using both controlled synthetic and actual historical earthquake records, confirming NPC 5 criteria compliance.

V. REQUIRED ESDS ARCHITECTURE: HYBRID ISOLATION PLATFORM

The ESDS platform will be developed as a multi-layered structure optimized for the specific footprint and total mass (M_{eq}) of commercial dialysis units. The passive component will utilize low-friction stainless steel friction sliders or rolling elements to support the static load and initiate isolation.[23] This component is designed to achieve the necessary period shift without active control, serving as the failsafe.

The semi-active damping system will be integrated using four (4) custom-designed, small-scale Magnetorheological (MR) dampers placed diagonally or horizontally between the isolation platform and the supporting building floor.[5] This configuration provides damping capacity across two horizontal translational degrees of freedom (DOF). The real-time control system requires a robust sensor package, including:
(1) accelerometers placed on the building floor to measure seismic input,
(2) accelerometers on the isolated platform to measure output acceleration (PEA), and
(3) displacement sensors or highly sensitive strain sensors to measure the relative stroke between the platform and the floor.
Strain sensors have demonstrated superior suppression effects in hybrid isolation systems compared to acceleration sensors alone, offering greater potential for practical engineering applications. The foundation of passive seismic isolation lies in shifting the natural fundamental period of a structure away from the dominant damaging frequencies of ground motion. This decoupling significantly reduces the acceleration transmitted to the isolated system, thereby protecting sensitive equipment. Passive isolation systems have been successfully implemented in protecting critical components such as raised-floor systems for computer racks, precision instruments, and even cultural artifacts. These systems typically utilize combinations of **friction sliders, rubber bearings, and viscous dampers**, each tuned to the specific mass and dynamic properties of the protected item.

For medical devices like dialysis machines, this technology provides an effective first line of defense against earthquake-induced accelerations. The inherent reliability and independence from external power sources make passive systems highly suitable for critical healthcare applications, where failure is unacceptable. However, the performance of purely passive systems is limited by their fixed tuning characteristics. Once designed for a specific natural frequency, they cannot adapt to varying seismic intensities, from moderate Design Basis Earthquakes (DBE) to severe Maximum Considered Earthquakes (MCE). Furthermore, the reduction in acceleration achieved by lowering stiffness often results in **large relative displacements**, increasing the risk of collisions with surrounding infrastructure or damage to essential utilities such as water and power lines. In a hospital environment with tightly packed equipment, these displacements can be catastrophic.

B. Semi-Active Control Systems and Magnetorheological (MR) Dampers

To overcome these inherent limitations, **semi-active control technologies** have emerged as an adaptable and energy-efficient alternative. Semi-active systems combine the adaptability of active systems with the reliability of passive systems, maintaining stability by dissipating—rather than injecting—energy. Among these, **Magnetorheological (MR) dampers** have gained prominence due to their simplicity, rapid response, and electrical failsafe feature, reverting to a passive state upon power loss.

MR dampers operate by adjusting the yield stress of a magnetorheological fluid through a controlled magnetic field. This property allows the damping force to be instantly modified in response to real-time ground motion data. Research studies demonstrate that combining MR dampers with rolling pendulum or frictional isolation systems significantly improves vibration suppression for sensitive equipment mounted on raised floors. Such configurations effectively reduce acceleration and velocity responses while keeping relative displacement to a minimum—a crucial advantage for confined hospital environments where spatial constraints are strict.

To ensure accurate modeling of MR damper performance, **nonlinear hysteretic models** such as the **extended Bouc–Wen** or **Dahl models** are commonly applied. These models capture the complex mechanical and fluid interactions that define MR behavior under dynamic loading, enabling precise simulation of damping characteristics necessary for system design and optimization.

C. Justification for the Hybrid ESDS Architecture

Achieving **Non-Structural Performance Category 5 (NPC 5)** for life-sustaining equipment such as dialysis machines requires meeting two conflicting objectives: minimizing transmitted acceleration and minimizing relative displacement. A purely passive isolation system cannot satisfy both simultaneously across the full range of earthquake excitations. Consequently, the **hybrid ESDS architecture** was developed as a comprehensive solution that integrates the stability of passive elements with the adaptability of semi-active control.

In this hybrid system, **passive isolation bearings or lattice-based materials** provide fundamental load support and low-frequency isolation, while **semi-active MR dampers** dynamically modulate the damping force to constrain displacement during high-intensity events. The integration is governed by a **clipped-optimal control algorithm**, which continuously evaluates acceleration and displacement feedback to balance stiffness and damping. This method has demonstrated superior performance in maintaining both stability and functional integrity in raised-floor seismic protection applications.

The hybrid ESDS represents a novel synthesis of **mechanical design, fluid dynamics, and control engineering**, specifically optimized for critical medical applications. By maintaining operational continuity under Maximum Considered Earthquake (MCE) conditions, it ensures compliance with the stringent NPC 5 standard, offering a scalable, energy-efficient, and reliable seismic resilience solution for life-support equipment in modern hospitals.

VI. IMPLEMENTATION STEP

•**Advanced Computational Resources:** High-Performance Computing (HPC) clusters are required for the intensive processing demands of Nonlinear Time History Analysis (NLTHA) and coupled FSI simulations, which require numerous CPU hours per run. Licensed access to industry-standard CAE/FEM software, such as ANSYS Motion and Simcenter Nastran, is essential for structural dynamics and fluid analysis.29 The control development phase requires a robust MATLAB/Simulink environment for algorithm design and real-time controller simulation.

•**Experimental Validation Facility:** Access to a large-scale, multi-axis shake table facility is non-negotiable for validating the hybrid system under MCE-level loading. The required capabilities must exceed nominal laboratory standards to accurately replicate complex 3D seismic motions and torsional effects, which are critical for failure analysis.

***Laboratory Equipment:** A dedicated MR damper testing rig is needed for experimental characterization, allowing for the generation and analysis of force-velocity hysteresis loops essential for calibrating the nonlinear parameters in the Bouc-Wen/Dahl constitutive models.[25]

VII. CONCLUSION

The Earthquake-Stabilized Dialysis System (ESDS) represents a transformative solution for ensuring healthcare resilience in seismic regions. By integrating passive isolation bearings with semi-active Magnetorheological (MR) dampers and real-time clipped-optimal control, ESDS minimizes both vibration and displacement, ensuring uninterrupted dialysis operation even during Maximum Considered Earthquakes (MCE). Advanced Fluid-Structure Interaction (FSI) modeling further safeguards internal liquid reservoirs from failure, meeting the stringent Non-Structural Performance Category 5 (NPC 5) standard. Future developments include autonomous power and water modules, long-term durability studies, and standardization for commercial deployment. Overall, ESDS redefines medical equipment safety, shifting focus from structural survival to continuous, life-sustaining functionality during and after seismicdisasters.

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IX. BIBLIOGRAPHY

1. [4] Predictive scoring systems for dialysis need post-earthquake.
2. [3] Haemodialysis patient experiences and complications post-Türkiye earthquakes.
3. [1] Disruption of dialysis services due to natural disasters.
4. [2] Impact of power and water loss on dialysis machine contamination and closure.
5. [13] Non-Structural Performance Categories (NPC) for hospital equipment.
6. [9] SPC and NPC ratings defining hospital seismic resilience targets (NPC 5).
7. [15] Critical Care Area definition and NPC 3 requirements.
8. [16] Modifications to ASCE 7-16 for critical healthcare facilities.
9. [14] Earthquake damage simulation to medical equipment (shaking table tests).
10. [7] Dynamic analysis of liquid-filled containers and FSI effects.
11. [8] Dynamic analysis of liquid storage cylindrical tanks (impulsive/convective actions).
12. [17] Small-scale base isolation for essential equipment protection.

X. REFERENCES

1. [1] Natural Disasters in the Americas, Dialysis Patients, and Implications for Emergency Planning: A Systematic Review - CDC, https://www.cdc.gov/pcd/issues/2020/19_0430.htm
2. 2. Reopening Dialysis Clinics after Restoration of Power and Water - FDA, https://www.fda.gov/medical-devices/emergency-situations-medical-devices/reopening-dialysis -clinics-after-restoration-power-and-water
3. 3. A Study on the Challenges of Relocated Hemodialysis Patients Following the Kahramanmaraş Earthquake - Turkish Journal of Nephrology, https://turkjnephrol.org/Content/files/sayilar/444/TJN_20251046_nlm_new_indd.pdf
4. 4. External validation and comparison of SAFE QUAKE and dialysis score in earthquake related crush injuries - PMC - NIH, https://pmc.ncbi.nlm.nih.gov/articles/PMC12366352/ 5.
5. Seismic protection of vulnerable equipment with semi-active control by employing robust and clipped-optimal algorithms - International Journal of Civil Engineering, https://ijce.iust.ac.ir/article-1-879-en.pdf
6. 6. Review of Magnetorheological Damping Systems on a Seismic Building - MDPI, https://www.mdpi.com/2076-3417/11/19/9339
7. 7. A Dynamic Analysis Method of Liquid-Filled Containers Considering ..., https://www.mdpi.com/2076-3417/14/7/2688

8. 8. Dynamic Analysis of Liquid Storage Cylindrical Tanks due to Earthquake - ResearchGate, https://www.researchgate.net/publication/272615874_Dynamic_Analysis_of_Liquid_Storage_Cy lindrical_Tanks_due_to_Earthquake
9. 9. Structural and Non-Structural Performance Categories - HCAI, https://hcai.ca.gov/facilities/building-safety/seismic-compliance-and-safety/seismic-performan ce-ratings/
10. 10. Study on Shaking Table Test and Vulnerability Analysis of 220 kV Indoor Substation in High-Intensity Areas - MDPI, https://www.mdpi.com/2412-3811/10/5/119 11
11. . Shake Tables - Structural Engineering and Earthquake Simulation Laboratory, https://www.buffalo.edu/seesl/services/shake_tables.html