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Analysis and modeling of forced-damped vibrations and their applications in medicine

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Highlights

- The study explores how forced-damped vibrations can be applied in various medical contexts. This may include using vibrations for medical imaging techniques such as ultrasound or MRI, where vibrations are applied to the body to generate images of internal structures.
- Vibrations can also be utilized for tissue characterization, diagnosis of medical conditions, and therapeutic interventions such as vibration therapy for rehabilitation or pain management.

Abstract

Forced-damped vibrations are pivotal in various medical applications, significantly contributing to the examination of tissue mechanical properties, development of medical devices, and understanding of biological systems' complexities. These vibrations represent the dynamic behavior of systems subjected to external forces and damping, where an external force continues to act, and damping determines the rate of energy dissipation. Advanced exploration of damping properties has led to the creation of novel technologies and methods, enhancing our ability to probe and manipulate the complex mechanical dynamics of biological tissues.

Keywords: Analysis, modeling, damped vibrations, medicine

Introduction

Vibrational phenomena are ubiquitous in the medical field, observed in a myriad of contexts [1]. Defined as the repetitive oscillatory motion around a stable point, these phenomena range from the microscopic level to large structural scales [2, 3]. In healthcare, vibrations take various forms, including mechanical vibrations in medical equipment, acoustic vibrations affecting hearing, and electromagnetic vibrations utilized in imaging technologies like MRI [4-6]. Analyzing these vibrations is vital, as they influence the design and functionality of diagnostic instruments, imaging systems, and therapeutic devices [7].

Vibrations in medical devices are characterized by distinct mechanisms, leading to their categorization into free, forced, damped, and resonance vibrations [8-12]. This classification aids in understanding their unique behaviors and effects in medical settings [13]. Free vibrations occur without external force, while forced vibrations arise from external stimuli. Damped vibrations gradually lose energy, and resonance vibrations occur at a specific frequency [14]. This classification is particularly relevant in medical applications, influencing the design and operation of medical equipment, diagnostic procedures, and therapeutic devices [15, 16].

Free vibrations are initiated when a system is set into motion and allowed to oscillate without any external forces [17, 18]. This category of vibration is distinctly defined by the system's natural frequency, a property dictated by its mass and stiffness characteristics. In the realm of medical devices, understanding and analyzing free vibrations is crucial, particularly in the design and operation of medical devices and instruments. Independent oscillations can significantly influence both performance and accuracy [19]. The natural frequency is vital for

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understanding the intrinsic vibrational behavior of these systems in medical contexts [20].

Forced vibrations occur when an external force or stimulus is applied to a system, causing it to vibrate at a frequency that differs from its natural frequency [21, 22]. This vibration category is marked by its variability, including both periodic and non-periodic patterns [23, 24]. The system's response to forced vibrations is contingent upon the specific attributes of the forcing function and the inherent properties of the system [25-27]. Recognizing the effects of forced vibrations is essential in medical settings, as external forces can alter the behavior of medical devices, diagnostic tools, and therapeutic instruments [28-30]. A deep understanding of these vibrational dynamics is key to optimizing the design and function of medical systems, thereby ensuring better precision and effectiveness [31, 32].

Resonance vibrations occur when an external force or stimulus matches a system's natural frequency, leading to significantly amplified oscillations [33]. This enhancement of vibrations can result in excessive, potentially harmful oscillations [34, 35]. In the medical field, where precision and stability are crucial, uncontrolled resonance vibrations pose significant risks [36, 37]. Thus, effective control and improvements are essential to prevent the detrimental effects of increased vibrations on medical devices, instruments, and structures [38, 39].

Damped vibrations represent a convergence of engineering innovation and healthcare progress [40]. With their controlled and reduced oscillations, damped vibrations serve a critical and diverse role in medicine [41, 42]. From diagnostic instruments to therapeutic strategies, the incorporation of damped vibrations underscores a collaborative, multidisciplinary approach dedicated to enhancing patient care, refining diagnostic capabilities, and propelling the evolution of medical technologies [43-46]. This exploration delves into the varied applications of damped vibrations, highlighting their essential contribution to diagnostic processes, therapeutic approaches, and the overall goal of achieving optimal patient outcomes in the ever-evolving medical landscape [47, 48].

Furthermore, the researches majored in tissue engineering and regenerative medicine leverages controlled vibrations to foster cell growth and direct tissue regeneration processes [49]. The application of damped vibrations in biomechanics research contributes to a deeper understanding of human movement, aiding in the development of rehabilitation strategies and orthopedic interventions [50, 51].

Applications of damped vibration in medicine

Damped vibrations are applied diversely within the medical sector, encompassing areas such as diagnostic imaging, medical devices, tissue engineering, and biomechanics research. The strategic implementation and exploration of damping characteristics play a pivotal role in driving forward medical technology, enhancing diagnostic procedures, and refining therapeutic practices [52].

Medical imaging

In the realm of medical imaging, damped vibrations serve to bolster diagnostic precision. Techniques like elastography utilize damped vibrations to evaluate tissue stiffness, employing induced vibrations to gather data on the mechanical properties of tissues. This approach is invaluable for identifying irregularities or diseases in organs. Specifically, variations in liver stiffness assessed through this method can reveal conditions such as cirrhosis, showcasing the critical role of damped vibrations in diagnosing organ pathologies [52].

Ultrasound Imaging: Damped vibrations are integral to ultrasound imaging, where acoustic waves generate images of internal body structures. A deep understanding of the damping characteristics of tissues enhances the optimization of imaging techniques, leading to improved diagnostic accuracy [53].

MRI: In MRI, an appreciation of damped vibrations is crucial for the development of pulse sequences and optimizing image quality.

Biomechanics and tissue characterization

Damped vibrations are pivotal in biomechanics research, enabling the study of human body movement and its mechanical behaviors. This includes examining the damping properties of joints, bones, and soft tissues. Such researches, which are indispensable for crafting rehabilitation methods, elucidating injury mechanisms, and advancing the design of orthopedic implants [52].

Simulating damped vibrations in a hypothetical system offers a parallel to biomechanical systems or tissues, where variables such as mass, stiffness, and damping ratio are tailored to mirror the specific characteristics of the biomechanical system or tissue in focus (**Figure 1**).

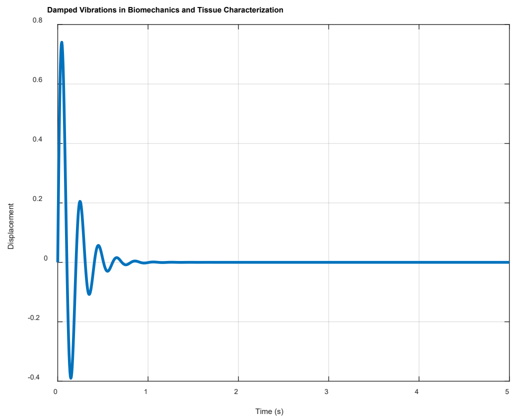

Figure 1. Damped vibration in biomechanics and tissue characterization.

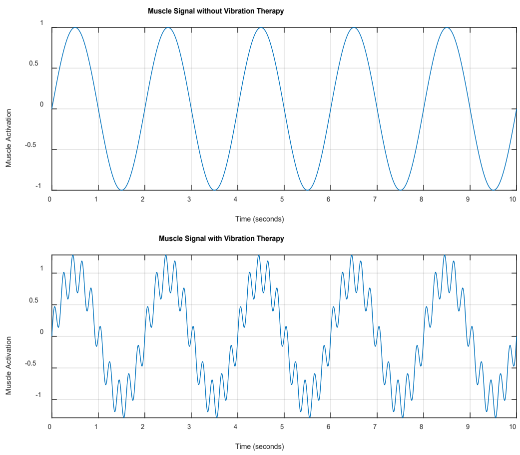

Figure 2. Representation of vibration therapy.

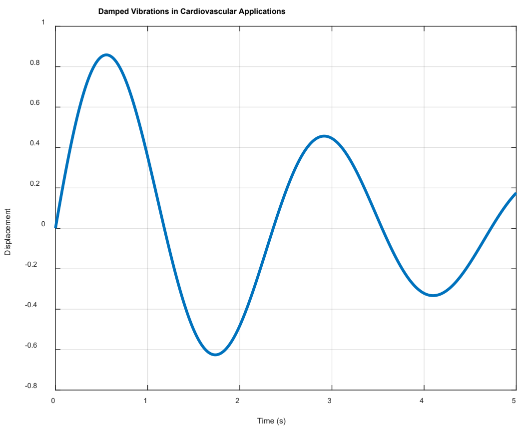

Figure 3. Damped vibration in cardiovascular application.

Figure 1 provides a detailed visualization of biomechanical systems or tissue characterization, underscoring the necessity of employing physiological parameters and a sophisticated model for accuracy. The integration of actual biomechanical data is crucial for augmenting the realism and reliability of our simulations.

Vibration therapy

Within the realm of medical treatments, vibration therapy leverages controlled vibrations for therapeutic benefits. This innovative therapy has been investigated for its potential to address a range of medical issues, particularly musculoskeletal disorders and rehabilitation needs. Although implementing vibration therapy requires a nuanced understanding and is often tailored to specific medical scenarios, a hypothetical MATLAB example offers a simplified model to demonstrate the principles of vibration therapy (**Figure 2**).

Figure 2 is a MATLAB example that simulates muscle signals over time to depict muscle activation both without and with vibration therapy. The lower subfigure introduces a controlled vibration signal, adding a sinusoidal component, to mimic the effects of vibration therapy on muscle activation. In practical scenarios, the selection of vibration parameters and their impact on muscle response are complex, necessitating thorough analysis and experimentation. MATLAB is extensively used by researchers and healthcare practitioners for advanced signal processing and analysis, enabling a comprehensive study of vibration therapy's effects on various physiological parameters [54].

Cardiovascular applications

Developing a detailed MATLAB application for modeling damped vibrations in cardiovascular applications entails intricate modeling and simulations, which extend beyond the topic of this review. The simulation of damped vibrations in a hypothetical system can serve as a model for cardiovascular dynamics, with adjustments to parameters like mass, stiffness, and damping ratio to reflect the specific characteristics of the cardiovascular system under study.

For a more precise modeling of cardiovascular dynamics, employing physiological parameters and a sophisticated model is essential (**Figure 3**). Furthermore, the inclusion of actual cardiovascular data would significantly improve the realism and accuracy of our simulations.

Figure 3 illustrates the specific behaviors of damped vibrations within a cardiovascular context, potentially showcasing the oscillatory movements within cardiovascular devices or systems. Such visualizations are crucial for understanding the dynamic aspects of cardiovascular mechanics.

Blood Flow Analysis: Damped vibrations are instrumental in analyzing blood flow dynamics, particularly in examining arterial elasticity and in the design and optimization of cardiovascu-

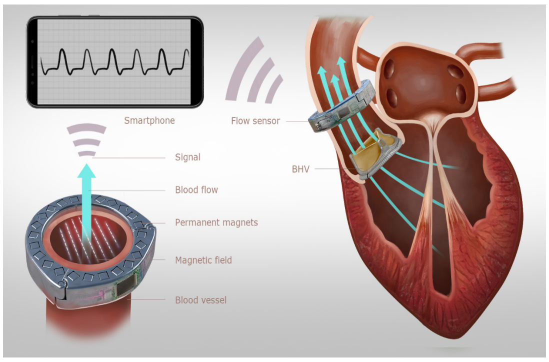

Figure 4. Prosthetic heart valves monitoring. The reference was cited from [56].

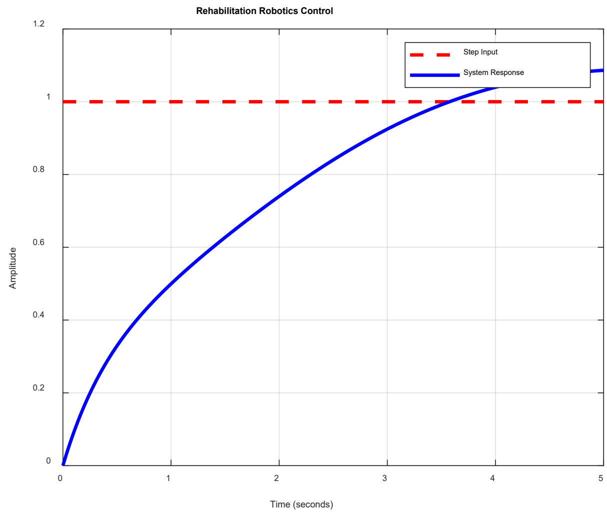

Figure 5. Results of a simple second-order plant model and a PID controller in a rehabilitation robotics.

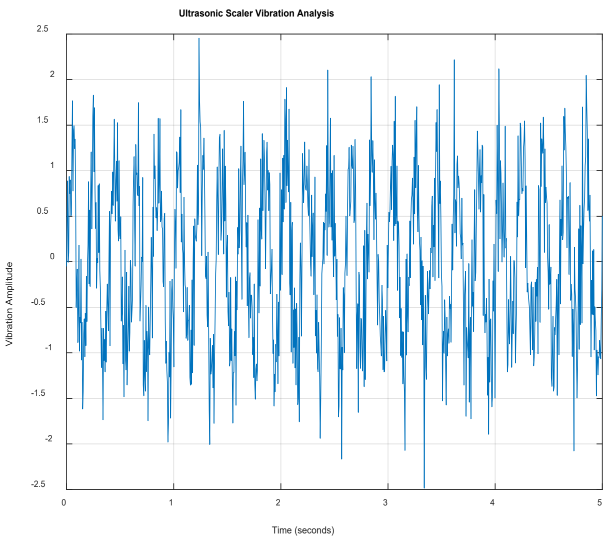

Figure 6. Vibration amplitude of ultrasonic scaler vibration analysis.

lar devices.

Heart Valve Dynamics: Analyzing the damped vibrations in heart valves aids in understanding their function and contributes to the development of artificial heart valves (see **Figure 4**).

Rehabilitation robotics

Rehabilitation robotics is tailored to meet a wide array of user needs, with damped vibrations playing a key role in enabling user-specific customization. This allows for adjustments to be made according to individual preferences, comfort levels, and specific rehabilitation goals, thereby enhancing both the user experience and the effectiveness of the rehabilitation process.

Incorporating advanced sensor technologies into robotic exoskeletons and assistive devices, and coupling these with damped vibrations, facilitate precise control and coordination. This integration ensures that devices can intelligently adapt to the user's movements and intentions. The strategic application of damped vibrations within rehabilitation robotics significantly boosts the success of rehabilitation programs. By offering a controlled and comfortable setting for movement, individuals in rehabilitation are able to participate more fully in therapeutic exercises, leading to improved recovery outcomes [54].

Ensuring a comfortable and safe experience is crucial for the acceptance and compliance with rehabilitation robotics. Damped vibrations are instrumental in fostering a positive interaction between the user and the robotic device, enhancing user engagement in rehabilitation activities and potentially accelerating recovery [55].

Rehabilitation robotics frequently employs MATLAB for control system design, data analysis, and simulation tasks. **Figure 5** illustrates the results of such simulations.

Figure 5 serves as a graphical representation that showcases the outcomes and performance of a control system in rehabilitation robotics, featuring a straightforward second-order plant model paired with a PID controller. The details depicted within the figure provide valuable insights into the control system's dynamic behavior and its effectiveness within a rehabilitative setting.

Dental applications

Tooth vibration analysis employs specialized instruments designed to initiate controlled vibrations and accurately measure the ensuing responses. These measurements yield crucial data regarding the dynamic behavior of teeth under various dental interventions.

For instance, during tooth drilling procedures, the interaction between dental instruments

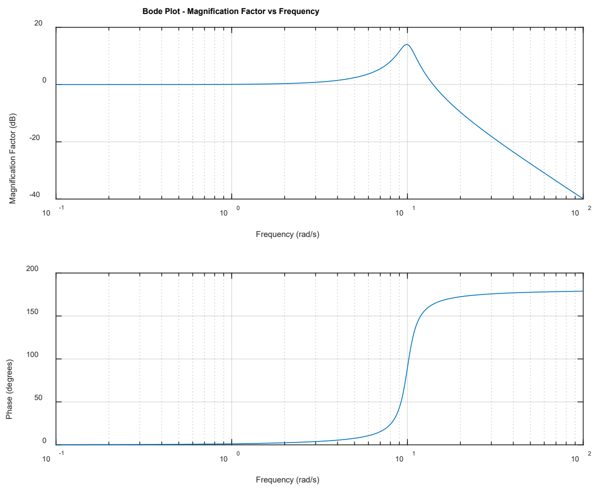

Figure 7. Bode diagram of the magnification factor.

and the tooth structure gives rise to vibrations. Through damped vibration analysis, dentists gain a refined understanding of the mechanical responses of teeth to differing procedures, enhancing both diagnostic capabilities and treatment precision [55].

The process of analyzing vibration amplitudes from an ultrasonic scaler with MATLAB typically involves the manipulation and graphical representation of data derived from the scaler's vibrations. **Figure 6** illustrates the simulation outcomes for the ultrasonic scaler application [55].

Figure 6 delves into the analysis of vibration amplitude in an ultrasonic scaler, offering critical insights that are essential for the optimization of the scaler's design, performance, and safety in dental or medical contexts.

The analysis of tooth vibrations aids in the assessment of structural integrity. Variations in vibration patterns can signal the presence of dental conditions such as cavities, cracks, or structural abnormalities. Such detailed information is invaluable to dentists for accurate diagnosis and the formulation of effective treatment plans [55].

Continued advancements in tooth vibration analysis are driving the development of new dental technologies and methodologies. This research-centric approach is pivotal in refining dental procedures, elevating diagnostic precision, and progressing the field of dental care.

Moreover, integrating tooth vibration analysis into dental education is crucial for the comprehensive training of future dental professionals. It equips aspiring dentists with a deep understanding of the mechanical dynamics involved in dental procedures, promoting a more knowledgeable and proficient approach to patient care [55].

Magnification factor

The magnification factor, also known as the amplification factor or gain, is crucial in understanding how a dynamic system amplifies or attenuates input vibrations at specific frequencies. It is typically depicted as a function of frequency, illustrating the system's behavior over a spectrum of frequencies [56].

In the context of a linear, single-degree-of-freedom system subjected to forced-damped vibrations, the magnification factor (M) is commonly defined as the ratio of the response amplitude (X) to the amplitude of the applied force (F_0). This relationship is mathematically represented as [38]:

$$M(\omega) = X/F_0 \qquad (1)$$

This formula of magnification factor is expressed as:

$$M(\omega) = 1/[(1 - (\omega/\omega_n)^2)^2 + (2\zeta\omega/\omega_n)^2]^{1/2} \qquad (2)$$

Where:
ω is the frequency of the input vibration.
ωn is the natural frequency of the system.
ζ is the damping ratio

The magnification factor is affected by the natural frequency and damping ratio of the system. When plotted against frequency, the Bode plot allows engineers and researchers to analyze how the system responds to different input frequencies. A peak in the magnification factor indicates resonance, where the system's response is magnified (see **Figure 7**).

The Bode diagram showcasing the magnification factor as a function of frequency offers a comprehensive representation of a dynamic system's response characteristics. This graphical representation is invaluable in analyzing structural, mechanical systems, and vibrational behaviors, providing critical insights into how these systems respond to varying frequencies.

Conclusion

Damping is paramount in the realm of forced-damped vibrations, serving to dissipate energy and diminish the amplitude of oscillations over time. The presence of various damping forms, such as friction or fluid resistance, influences a system's response, guiding it towards equilibrium. Forced-damped vibrations are described through mathematical models, typically differential equations, facilitating a deep understanding of the system's dynamics. This includes insights into steady-state and transient responses, resonance frequencies, and additional pivotal properties.

The exploration of forced-damped vibrations enables engineers to design resilient structures, enhance machine efficiency, and ensure the stability and safety of mechanical systems. Furthermore, the application of damped vibrations in medicine emerges as a critical and multifaceted component of healthcare and biomedical research. Through the investigation of damped vibrations, significant advancements have been made, particularly in understanding the mechanical properties of biological tissues. This knowledge is instrumental across a wide range of medical applications, underscoring the indispensable role of damped vibrations in advancing healthcare.

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