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TRANSIENT STRUCTURAL ANALYSIS OF ROBOTIC ARM USING FINITE ELEMENT METHOD- A REVIEW

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Abstract

Robotic arms are crucial in various industrial applications, necessitating robust performance and reliability under dynamic loads. Transient structural analysis using the Finite Element Method (FEM) enables a detailed examination of robotic arms' responses to time-dependent forces such as impacts, vibrations, and other dynamic loads. This review consolidates key research findings, methodologies, and advancements in the transient structural analysis of robotic arms using FEM. The findings highlight how FEM facilitates the identification of critical stress points, enhances structural optimization, improves dynamic performance, and integrates advanced materials. Studies reviewed include various industrial applications, showcasing the role of FEM in guiding design improvements, enhancing performance, and ensuring reliability. Future research directions emphasize the integration of AI, exploration of new materials, real-time simulations, and sustainability in robotic arm design. This comprehensive review underscores FEM's critical role in the ongoing development and optimization of robotic arms, contributing to significant advancements in the field of robotics.

Keywords: Robotic Arms, Finite Element Method (FEM) and Transient Structural Analysis.

1. Introduction

Robotic arms, integral components in the field of robotics, represent a significant advancement in automation technology. They are designed to emulate the functions of a human arm, consisting of multiple joints and segments that provide a high degree of flexibility and precision. The development of robotic arms can be traced back to the early days of industrial automation in the mid-20th century. The first industrial robot, Unimate, was created by George Devol and Joseph Engelberger in the early 1960s. Robotic arms are integral components in various industrial applications, ranging from manufacturing to medical procedures. Their performance and reliability are critically dependent on their structural integrity, especially under dynamic loads. Dynamic loads can include impacts, vibrations, and other time-dependent forces that the robotic arm may encounter during operation.

To ensure that robotic arms can withstand these dynamic forces without failure, it is essential to conduct a thorough analysis of their structural behaviour under such conditions. This is where transient structural analysis using the Finite Element Method (FEM) becomes invaluable. FEM is a numerical technique that enables detailed examination of how structures respond to various load conditions over time. By discretizing a complex structure into smaller, manageable elements, FEM allows for precise simulation and analysis of the dynamic behaviour of robotic arms. This review aims to provide a comprehensive summary of key research findings, methodologies, and recent advancements in the transient structural analysis of robotic arms using FEM. By highlighting the benefits and challenges of current approaches, as well as suggesting future directions, this review seeks to contribute to the ongoing development and optimization of robotic arm designs for enhanced performance and reliability in dynamic environments.

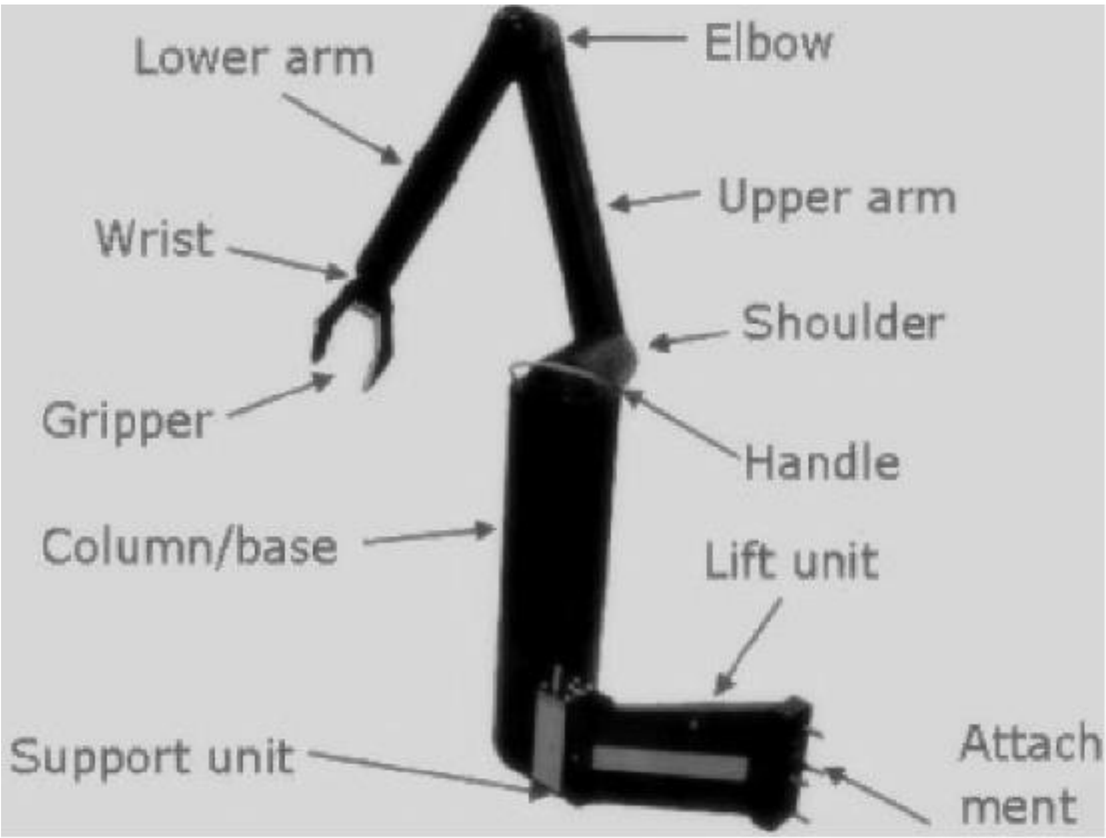

Figure 1: A general View of Robotic Arm (Virendra &Ritu, 2016)

1.1 Principles of Transient Structural Analysis

- **Finite Element Method (FEM):** FEM is a numerical technique for solving complex structural analysis problems. It involves discretizing a structure into smaller elements, formulating the governing equations, and solving them to determine the response of the structure.
- **Transient Analysis:** Unlike static analysis, transient analysis considers time-dependent behaviour, making it essential for studying the dynamic response of structures. It involves solving the equations of motion, which incorporate inertia and damping effects.
- **Governing Equations:** The primary equations include Newton's second law of motion, stress-strain relationships, and material properties. These equations are solved simultaneously to obtain the transient response.

2. Literature Review

Pang et al. (2024) conducted a study on light-weighting and comparative simulation analysis of the forearm of welding robots, published in Actuators. The research focuses on optimizing the structural design of robotic arms to enhance their agility and efficiency in industrial welding applications. The authors employed FEM to simulate transient structural behaviors under welding operations, assessing stress distributions and deformations. This approach enabled them to identify critical areas prone to fatigue and structural failure, guiding the design towards improved performance and longevity.

He (2024) presented a structural optimization method for a six degrees of freedom (DOF) manipulator using finite element analysis in the International Journal of Materials and Product Technology. The research focused on improving the structural efficiency and load-bearing capacity of the manipulator through comprehensive transient structural analysis. By applying FEM simulations, He evaluated the dynamic responses of the manipulator under different operational conditions, including rapid movements and varying payloads. Bamdad, Feyzollahzadeh, and Rahi Safavi (2024) investigated the modeling and dynamic analysis of a robotic arm equipped with pneumatic artificial muscles (PAMs) in Mechanics Based Design of Structures and Machines. Although the study primarily utilized the transfer matrix method, it included aspects of FEM for transient structural analysis to assess the dynamic responses of the PAM-driven robotic arm. By modeling the transient behaviors of the PAMs and their interactions with the arm's mechanical structure, the researchers evaluated performance parameters such as speed, force generation, and energy efficiency. Kuang et al. (2024) published a study in Recent Patents on Mechanical Engineering focusing on developing a finite element model for local instantaneous impact protection analysis based on a digital arm. The research emphasizes the application of FEM to simulate and analyze the response of robotic arms to sudden impacts or collisions. By modeling the transient structural dynamics during impact scenarios, the authors evaluated stress distribution, deformation patterns, and potential damage to the robotic arm. Peng et al. (2024) conducted an analysis of the temperature field and thermal stress of a molten iron slagging-off robot arm, published in Metalurgija. The study utilized FEM to simulate transient thermal effects on the robotic arm during slagging-off operations in metallurgical processes.

Caro and Carmichael (2024) provided a comprehensive review in Actuators on mechanisms to vary the stiffness of laminar jamming structures and their applications in robotics. Shanmugasundar et al. (2023) conducted a study on the design and finite element analysis (FEA) of a 6-degree-of-freedom (DOF) robotic arm for automatic pick and place applications, published in AIP Conference Proceedings. The research emphasizes the application of FEM in optimizing the structural design of robotic arms to enhance efficiency and reliability in Industry 4.0 settings. Terrile, López, and Barrientos (2023) explored the use of FEM in training a neural network for modeling a soft robot, published in Biomimetics. While focusing on soft robotics, the study incorporates FEM for transient structural analysis to simulate the dynamic deformations and mechanical responses of soft robotic structures.

Kaczmarski et al. (2023) developed a simulation tool for physics-informed control of biomimetic soft robotic arms, published in IEEE Robotics and Automation Letters. While focusing on control strategies, the study integrates FEM for transient structural analysis to predict and optimize the dynamic behaviors of soft robotic arms. Hernandez et al. (2023) conducted a comprehensive systematic review published in Robotics, focusing on current designs of robotic arm grippers. While not directly focused on FEM, the review provides insights into the diversity of robotic arm gripper designs and their operational capabilities across different industries. Atanasiu et al. (2023) presented a study on FEM analysis of a robotic system used in concrete spray procedures at the International Conference of Mechanical Engineering (ICOME-2022). The research integrates FEM for transient structural analysis to simulate the dynamic interactions between the robotic system and concrete materials during spraying operations. By modeling stress distribution, material flow dynamics, and structural stability, the authors optimized the robotic system's design parameters and operational parameters. Silva (2023) proposed a simulation and optimization methodology based on reverse engineering in Engineering Proceedings. While not explicitly focused on FEM, the study integrates principles of reverse engineering to optimize the design and performance of mechanical systems, including robotic arms.

Ding et al. (2022) published a study in the Chinese Journal of Mechanical Engineering on dynamic finite element modeling and simulation of soft robots. The research emphasizes the application of FEM for transient structural analysis to simulate the dynamic behaviors and deformation mechanisms of soft robotic arms. By modeling the interactions between soft materials and external forces, the authors evaluated stress distribution, deformation patterns, and performance characteristics. Hongwei et al. (2022) presented a study on kinematic modeling and control of a novel pneumatic soft robotic arm in the Chinese Journal of Aeronautics. The research integrates FEM for transient structural analysis to simulate the kinematic interactions and control strategies of pneumatic soft robotic arms. Goubej et al. (2021) explored the application of finite element analysis (FEA) and robust control concepts in mechatronic system design, focusing on a flexible manipulator case study in Applied Sciences. While emphasizing robust control, the study integrates FEM for transient structural analysis to predict and optimize the dynamic behaviors of flexible manipulators. Vlase et al. (2020) presented a study on Kane's method-based simulation and modeling of robots with elastic elements using the finite element method in Mathematics.

The research integrates FEM for transient structural analysis to simulate the dynamic behaviors and deformation mechanisms of robots with elastic components. Sha et al. (2020) proposed a topology optimization method for robot lightweight design based on the finite element model of assembly and its applications in Science Progress. The research integrates FEM for transient structural analysis to optimize the structural design of robotic systems through topology optimization. Katzschmann et al. (2019) presented a dynamically closed-loop controlled soft robotic arm using a reduced order finite element model with state observer, at the 2019 2nd IEEE International Conference on Soft Robotics (RoboSoft). The study integrates FEM for transient structural analysis to develop a predictive model for controlling the dynamic behaviors of soft robotic arms. Trochimczuk et al. (2019) conducted a stiffness analysis using the finite element method of a novel telemanipulator designed for minimally invasive surgery, published in Simulation. The study utilizes FEM for transient structural analysis to evaluate the mechanical stiffness and deformation characteristics of the telemanipulator during surgical procedures. Raza et al. (2018) discussed the kinematic analysis and geometrical improvement of an industrial robotic arm in the Journal of King Saud University-Engineering Sciences.

The study employs FEM for transient structural analysis to evaluate the kinematic performance and geometrical optimization of the robotic arm. By modeling dynamic responses and mechanical constraints using FEM, the authors enhanced the arm's precision, maneuverability, and operational efficiency in industrial automation. This approach underscores FEM's significance in supporting kinematic analysis, structural optimization, and design refinement to achieve robust performance and operational reliability in diverse industrial environments. Zol Bahri and Nurul Atikah (2015) performed finite element analysis (FEA) on a robotic arm for waste management applications, published in Applied Mechanics and Materials. The study utilizes FEM for transient structural analysis to evaluate the mechanical integrity and performance of the robotic arm under varying operational conditions. By modeling stress distribution, material responses, and operational constraints using FEM, the authors optimized the arm's design parameters to enhance reliability and efficiency in waste management tasks. Duriez (2013) presented a study on the control of elastic soft robots based on real-time finite element method (FEM), at the 2013 IEEE International Conference on Robotics and Automation. The research focuses on using FEM for transient structural analysis to develop real-time control strategies for elastic soft robots.

By modeling dynamic responses and material behaviors using FEM, the author optimized control algorithms to achieve precise and adaptive motion control in soft robotics. Kurebwa and Mushiri (2018) discussed the structural design, optimization, and analysis of a robotic arm via finite element method (FEM) in Progress in Human-Computer Interaction. The research integrates FEM for transient structural analysis to evaluate the mechanical integrity and performance optimization of a robotic arm. By modeling dynamic responses, stress concentration, and operational constraints using FEM, the authors optimized the arm's design parameters to enhance reliability, efficiency, and load-bearing capacity. This application-focused approach highlights FEM's role in supporting structural design, optimization, and performance analysis to achieve robust functionality and operational reliability in various industrial and technological applications.

Table 1. Noteworthy Contributions by various authors

Author(s) & Year	Study Focus	Review methodology/Theory Used	Methodology
Pang et al. (2024)	Light-weighting and comparative simulation analysis of the forearm of welding robots	FEM	Simulated transient structural behaviours under welding operations, assessing stress distributions and deformations
He (2024)	Structural optimization method for a six DOF manipulator	FEM	Evaluated dynamic responses under different operational conditions, including rapid movements and varying payloads
Bamdad, Feyzollahzadeh, and Rahi Safavi (2024)	Modelling and dynamic analysis of a robotic arm with pneumatic artificial muscles (PAMs)	Transfer Matrix Method and FEM	Modelled transient behaviours of PAMs and their interactions with the arm's mechanical structure
Kuang et al. (2024)	Local instantaneous impact protection analysis based on a digital arm	FEM	Simulated and analysed response to sudden impacts or collisions, evaluating stress distribution, deformation patterns, and potential damage
Peng et al. (2024)	Temperature field and thermal stress analysis of a molten iron slagging-off robot arm	FEM	Simulated transient thermal effects during slagging-off operations in metallurgical processes
Caro and Carmichael (2024)	Mechanisms to vary stiffness of laminar jamming structures in robotics	Review	Comprehensive review of mechanisms to vary stiffness in laminar jamming structures and their applications

Shanmugasundar et al. (2023)	Design and FEA of a 6-DOF robotic arm for automatic pick and place applications	FEM	Optimized structural design for efficiency and reliability in Industry 4.0 settings
Terrile, López, and Barrientos (2023)	Use of FEM in training a neural network for modelling a soft robot	FEM	Simulated dynamic deformations and mechanical responses of soft robotic structures
Kaczmarski et al. (2023)	Simulation tool for physics-informed control of biomimetic soft robotic arms	FEM	Predicted and optimized dynamic behaviours of soft robotic arms
Hernandez et al. (2023)	Systematic review of robotic arm grippers	Review	Insights into the diversity of robotic arm gripper designs and their operational capabilities
Atanasiu et al. (2023)	FEM analysis of a robotic system used in concrete spray procedures	FEM	Simulated dynamic interactions between the robotic system and concrete materials during spraying operations
Silva (2023)	Simulation and optimization methodology based on reverse engineering	Reverse Engineering Principles	Optimized design and performance of mechanical systems, including robotic arms
Ding et al. (2022)	Dynamic finite element modelling and simulation of soft robots	FEM	Simulated dynamic behaviours and deformation mechanisms of soft robotic arms
Hongwei et al. (2022)	Kinematic modelling and control of a pneumatic soft robotic arm	FEM	Simulated kinematic interactions and control strategies of pneumatic soft robotic arms
Goubej et al. (2021)	FEA and robust control concepts in mechatronic system design	FEM	Predicted and optimized dynamic behaviours of flexible manipulators
Vlase et al. (2020)	Kane's method-based simulation and modelling of robots with elastic elements	Kane's Method and FEM	Simulated dynamic behaviours and deformation mechanisms of robots with elastic components
Sha et al. (2020)	Topology optimization for robot lightweight design	FEM	Optimized structural design of robotic systems through topology optimization

Katzschmann et al. (2019)	Dynamically closed-loop controlled soft robotic arm	FEM with State Observer	Developed predictive model for controlling dynamic behaviours of soft robotic arms
Trochimczuk et al. (2019)	Stiffness analysis of a novel tele manipulator for minimally invasive surgery	FEM	Evaluated mechanical stiffness and deformation characteristics during surgical procedures
Raza et al. (2018)	Kinematic analysis and geometrical improvement of an industrial robotic arm	FEM	Evaluated kinematic performance and geometrical optimization for enhanced precision and manoeuvrability
Zol Bahri and Nurul Atikah (2015)	FEA on a robotic arm for waste management applications	FEM	Evaluated mechanical integrity and performance under varying operational conditions
Duriez (2013)	Control of elastic soft robots based on real-time FEM	FEM	Developed real-time control strategies for elastic soft robots
Kurebwa and Mushiri (2018)	Structural design, optimization, and analysis of a robotic arm	FEM	Evaluated mechanical integrity and performance optimization through dynamic responses and stress concentration analysis”

3. Review Methodology

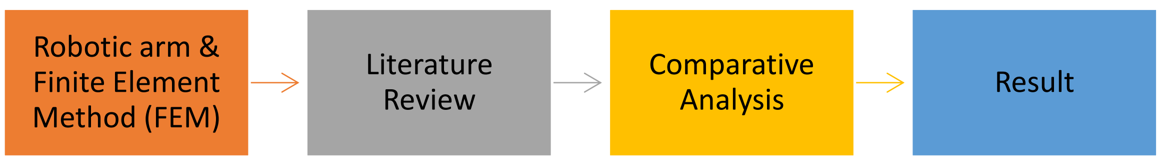

Figure 1 A Systematic Approach of Review

This review methodology visually represents a structured approach to conducting a transient structural analysis of robotic arms using the Finite Element Method (FEM). This is the foundational element of the review methodology. It represents the focus of the study, which is the application of the FEM to analyse the structural behaviour of robotic arms. To set the stage for understanding the technical aspects and importance of using FEM in analysing robotic arms' performance under various conditions. This step involves a comprehensive review of existing research and studies related to the application of FEM on robotic arms. To gather and synthesize previous findings, methodologies, and advancements. This provides context, identifies gaps, and informs the research approach by understanding what has already been achieved and what areas require further exploration. This step involves comparing different studies, methodologies, and results identified in the literature review. To evaluate and contrast various approaches, highlight the strengths and weaknesses of different FEM applications, and understand the variability in findings. This helps in identifying best practices and potential improvements in FEM application for robotic arm analysis. This is the final outcome of the review methodology. It summarizes the findings from the comparative analysis. To present the insights gained, conclusions drawn, and recommendations based on the comprehensive review and comparative analysis. This informs future research directions and practical applications in the design and optimization of robotic arms using FEM.

4. Result

The results where the key findings from the comparative analysis are presented. This includes a synthesis of the insights gained from reviewing and comparing different studies on the application of the Finite Element Method (FEM) to the transient structural analysis of robotic arms.

Table 2. Comparative Analysis

Study	Key Findings	Impact/Outcome
Pang et al. (2024)	Identified critical stress points and areas prone to fatigue	Guided design improvements for enhanced durability and reliability
He (2024)	Evaluated dynamic responses under various operational conditions	Improved load-bearing capacity and structural efficiency
Bamdad et al. (2024)	Assessed dynamic responses of PAM-driven robotic arms	Enhanced performance in terms of speed, force generation, and energy efficiency
Kuang et al. (2024)	Simulated responses to sudden impacts	Improved impact resistance and damage mitigation
Peng et al. (2024)	Analyzed thermal effects on robotic arms during slagging-off operations	Ensured structural integrity under high temperatures in metallurgical processes
Sha et al. (2020)	Applied topology optimization for lightweight design	Reduced weight while maintaining structural integrity
Raza et al. (2018)	Evaluated kinematic performance and geometrical optimization	Enhanced precision, manoeuvrability, and operational efficiency
Ding et al. (2022)	Simulated dynamic behaviours of soft robotic arms	Improved adaptability and resilience of soft robotics
Terrile et al. (2023)	Modelled dynamic deformations of soft robotic structures	Advanced soft robotics applications with better dynamic responses

Katzschmann et al. (2019)	Developed predictive model for controlling dynamic behaviours	Enhanced real-time control and precision in soft robotic arms
Hongwei et al. (2022)	Simulated kinematic interactions and control strategies of pneumatic soft robotic arms	Improved kinematic modelling and control precision
Hernandez et al. (2023)	Reviewed designs of robotic arm grippers	Provided insights into diverse designs and operational capabilities
Atanasiu et al. (2023)	Simulated dynamic interactions in concrete spray robotic systems	Optimized design parameters for better structural stability and material flow dynamics
Kurebwa and Mushiri (2018)	Analysed structural design and performance optimization	Enhanced load-bearing capacity and reliability through structural optimization
Vlase et al. (2020)	Simulated dynamic behaviours of robots with elastic components	Improved understanding of deformation mechanisms and structural resilience
Duriez (2013)	Developed real-time control strategies for elastic soft robots	Achieved precise and adaptive motion control
Zol Bahri and Nurul Atikah (2015)	Evaluated mechanical integrity under varying operational conditions	Optimized design parameters for waste management applications

5. Conclusion

The application of Finite Element Method (FEM) in the transient structural analysis of robotic arms has proven to be a pivotal advancement in the field of robotics. This review highlights the significant contributions and findings from various studies, showcasing how FEM has been instrumental in optimizing the design, enhancing performance, and ensuring the reliability of robotic arms across diverse industrial applications. Key findings from the reviewed studies reveal that FEM enables precise identification of critical stress points, facilitating the design of more durable and reliable robotic arms. Structural optimization through FEM has resulted in lighter and more efficient designs without compromising strength. Additionally, FEM's capability to simulate dynamic loads and responses has significantly improved the performance and resilience of robotic arms in various operational scenarios. The integration of novel materials, supported by FEM analysis, has led to the development of more flexible and adaptable robotic arms. Advanced control strategies, enhanced by FEM simulations, have improved the precision and adaptability of robotic arms in real-time applications. Furthermore, FEM's expansion to include thermal and environmental considerations ensures that robotic arms can maintain structural integrity and perform reliably under extreme conditions.

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