



Dynamic Analysis of Mechanisms with Flexible Connections

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Annotation

This article is devoted to the analysis of the dynamics of mechanisms with flexible connections. Flexible joints are widely used in mechanical design, in areas such as robotics and aerospace. The article examines the stress, deformation and dynamic state of flexible connections, as well as their impact on the stability of systems. In addition, various mathematical models such as Lagrangian and Hamiltonian methods are discussed, which are used to ensure the strength and stability of the mechanism. Based on experimental data, the practical applications of the mechanisms, especially in robotics and aerospace, are analyzed, as well as the advances that can be achieved. Future research and development of new technologies, materials and control systems are essential to improve the efficiency of flexible joint.

Keywords: flexible connections, dynamics of mechanisms, strength and stability, robotics, aerospace industry, dynamic analysis, Lagrangian methods, Hamiltonian methods, materials, stability of systems, composite materials, finite element method (FEM).



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INTRODUCTION

Mechanisms are devices used to transmit motion, direct force and moment from one point to another, and to control energy and motion. There are several types of mechanisms, for example, rigid-body mechanisms and flexible-joint mechanisms.

Rigidly coupled mechanisms typically transmit movement accurately and completely because they have minimal deformation or elasticity. However, in many practical systems, especially in robotics, aerospace and automation, the elastic properties of connections (i.e. flexibility) play an important role.

Flexible joint mechanisms are very complex systems due to their dynamic characteristics. These systems introduce deformations as they transmit motion and force, requiring more careful and consistent analysis than traditional rigid joint systems. Flexible connections introduce elasticity, deformation, and temporary forces into the mechanism, which makes the dynamics of the system much more complex compared to mechanisms with rigid connections.

The analysis of such mechanisms is of great importance because they are widely used in the real world, such as in cars, airplanes and other high-tech devices. For example, in the field of robotics, the use of mechanisms with flexible joints and the study of their movement and dynamic

characteristics allows the development of robots with high precision, as well as increasing their speed, stability and energy efficiency. In the aerospace industry, it is necessary to study the elastic properties of joints in rockets or aircraft, correctly analyze their dynamics and take into account aerodynamic characteristics.

Studying the dynamic analysis of flexible joint systems allows one to fully understand their elastic properties and effectively control motion. When systems are subjected to changing forces or external influences, the elastic responses of the joints have a significant impact on the overall movement of the mechanism. Therefore, the dynamics of mechanisms with flexible connections and the methodology for their analysis are an important aspect for each engineering system.

This article discusses the dynamics of mechanisms with flexible joints and the corresponding methods for their analysis. Modeling the motion of systems, calculating forces and deformations using mathematical and physical methods, as well as the application of these mechanisms in real examples are covered in the article. The goal is to simplify the analysis of flexible joint mechanisms and increase understanding of their operation in practice.

Theoretical foundations. In mechanical systems, joints play an important role in transmitting motion and controlling forces and moments. In traditional connections (rigid connections), the movement of mechanisms is often based on a constant and strict geometry, that is, the angle and distance between the connections always remains the same. However, in a system with flexible connections, the connections have elastic (or deformable) properties, which significantly complicates the dynamics of the mechanism.

The main characteristics of flexible connections are as follows:

1. Elastic properties: Flexible connections may deform. These connections cause elastic changes (eg, torsion, bending) between two or more elements. Such connections can significantly change the transfer of motion and forces in the mechanism compared to rigid connections.
2. Dynamic Responses: When flexible joints are in motion, they often cause changes in forces and deformations. These deformations often lead to characteristic oscillations and vibrations of the system, which affects the overall movement of the mechanism.
3. Forces and Moments: The movement of flexible joints is not limited to geometric changes only, but also requires consideration of elastic force effects. For example, when flexible connections are twisted or deformed, they develop resistive moments that do not occur in rigid connections.
4. Reverse forces: When forces are applied to flexible joints, they return through reverse reactions (restoring forces) to the deformed joints. These reverse forces may be due to stress, compression, or other mechanical conditions. Their calculation usually requires monitoring the elastic properties of each connection.

These characteristics significantly complicate the analysis of mechanisms with flexible connections. To calculate their movement, stresses and deformations, it is necessary to use methods that differ from those used in systems with rigid connections.

Flexible joint mechanisms are mechanical systems connected through elastic (or deformable) joints. These mechanisms can mainly be divided into two types: rigid joint mechanisms and flexible joint mechanisms.

Mechanisms with flexible joints are widely used in robots and automated systems. For example, in robotic arms or maneuvering systems, flexible joints often enable fast and highly precise operation. Thus, mechanisms with flexible joints make the movement of robots more dynamic and adaptive. This type of mechanism is used mainly in operations that require high precision and elasticity, such as medical robots or precision assembly processes.

- Example: Robotic arms, especially manipulators, often have flexible joints that allow them to adapt and perform movements with high precision. These mechanisms use elastic connections to perform operations, but each movement requires consideration of deformation and elastic properties.

In the aerospace industry, mechanisms with flexible connections, unlike rigid ones, are deformed under the influence of external forces. Flexible joints provide elastic connections between moving parts of aerospace systems. They are, for example, used to reduce disruptions during rocket operation or when handling aerodynamic forces during flight.

- Example: An important aspect is to take into account the elastic properties of the wings of spacecraft or aircraft and elements of their mechanisms. These systems often have joints that deform under the influence of aerodynamic forces or external loads, which requires their dynamic analysis.

Mechanisms with flexible connections are also used in automotive and transportation systems. For example, in car suspensions it is necessary to take into account elastic connections that ensure movement on roads. These mechanisms help ensure ease of operation, stability and durability of vehicles.

- Example: Elastic elements in suspension systems (for example, springs or shock absorbers) provide elastic reactions when the vehicle moves. To accurately analyze the operation of such mechanisms, flexible connections must be taken into account.

Mechanisms with flexible connections are also found in industrial equipment. For example, conveyor systems or various mechanical drives use connections with elastic properties. These types of mechanisms usually interact with systems that operate at high speeds and have flexible connections. When performing dynamic analysis of mechanisms with flexible connections, it is important to consider the features and methodologies, since they have more deformations and elastic responses compared to traditional mechanisms with rigid connections.

Flexible joint mechanisms are types of mechanisms used in various physical systems, such as mechanical stops or systems of mechanical parts, where the joints are not rigid and are subject to movement and deformation. These systems are usually elastic, so deformations occur in response to physical forces. They are subjected to dynamic testing and it is important to determine how deformations affect movement.

When machines with flexible joints are in motion, their joints undergo changes: they stretch, bend or twist, resulting in deformations. These deformations, in turn, affect the dynamics of the mechanism, since:

- Deformed joints: The elastic (flexible) properties of joints change depending on the position of the joints and the impact of forces during movement.
- Stresses: Any deformation involves a force that can also affect the movement of the mechanism and other parts of the system. Flexible joints respond to both external and internal forces.

Lagrange and Hamilton methods:

Lagrange and Hamilton methods are widely used to analyze the dynamics of mechanical systems. Both methods play a key role in the mathematical description of mechanisms and modeling of their movement.

- Lagrange Method:** In the analysis of mechanisms using Lagrange, the energy system, namely kinetic energy and potential energy, are interrelated to describe the motion of the system. Lagrange's equations have the form:

$$L = T - V$$

where T is kinetic energy and V is potential energy. For flexible joints and their deformations, kinetic energy of motion (for example, torsion or tension of joints) and potential energy (elastic energy) are interrelated.

Using the Lagrange equations, differential equations of motion of the mechanism are formed, and the kinematics of the system is analyzed.

- **Hamilton's Method:** In Hamilton's method, the total energy of the system, that is, kinetic and potential energy, is used to describe motion. The Hamilton method is often used as an alternative to the Lagrange method, but it may be more convenient for controlling the state of the system (position and torque). Hamilton's formula looks like this:

$$H = T + V$$

where T is kinetic energy and V is potential energy. Hamilton's method allows one to effectively analyze the movement of joints and their elastic properties.

Physical and elastic model:

In mechanisms with flexible connections, a physical and elastic model are necessary to describe the motion of the system. Using this model, the elastic properties of connections (for example, elastic responses to forces) and the connections between connections (for example, their flexibility) are studied.

- **Physical model:** The movement of a mechanical system is determined through external forces, moments and other mechanical phenomena. When flexible connections deform in a physical state, the interaction of the connections and the influence of external forces must be taken into account.
- **Elastic model:** Elastic mechanisms are usually based on Hooke's law, that is, deformation (tension or compression) is proportional to external forces. Elastic models are used to describe the relationships between deformations and movements of a system.

Elasticity and Material Properties: Elastic materials (such as metal and plastic) are used to model the recovery of deformed joints and the reverse forces that arise when they move.

The dynamics of flexible joint mechanisms is a complex process that requires the analysis of motion through physical forces and energy exchange. Lagrange and Hamilton methods are powerful tools for mathematically modeling a system, allowing for a deeper understanding of joint deformations and energy exchange in the system. These analyzes are necessary to optimize and improve the performance of mechanical systems.

Strength and Stability Analysis:

Mechanisms with flexible joints, their deformations and movements usually constitute complex mechanical systems. To properly analyze the operation of these systems, it is necessary to study their strength and stability. These two aspects help to understand under what conditions the mechanism will work, and under what conditions it may malfunction or be destroyed.

Strength describes how a mechanism resists external forces or internal energy exchanges and whether it can recover. Mechanisms with flexible joints often have elastic properties that allow them to be resistant to external forces. The strength of such mechanisms is analyzed using various methods.

1. Elastic and plastic properties of materials:

- Elastic mechanism: Flexible joints are elastic and can recover their shape after deformation. Strength analysis uses models to determine the material's elastic modulus, random forces, and deformations. If the material deformation remains in the elastic region, the mechanism is restored.
- Plastic Mechanism: If forces exceed the elastic limit of a material, the material undergoes plastic deformation. In this case, the strength of the mechanism decreases, since it becomes difficult to restore the material after plastic deformation.

2. Strength analysis methods:

- Finite element method (FEM): Finite element method is widely used to analyze deformations and forces in mechanisms. This method allows each connection and part of the system to be divided into small elements and analyzed one by one.
- Dynamic Load Test: Used to test machinery under high speeds and loads to evaluate its strength and energy absorption capacity.

Stability analysis plays an important role in the motion analysis of a mechanism. Mechanisms with flexible joints often need to maintain their position under difficult conditions. The stability of a system helps to understand how it interacts with external forces, internal forces and deformations.

1. Stability and flexible connections:

The forces transmitted through flexible connections can significantly affect the stability of the system. If excessive forces are applied to the system, connections may become deformed or become difficult.

For example:

- If the forces are too great, the connections may bend or fail, causing the system to become unstable.
- If the forces are within normal limits, the connections retain their elastic properties and the system remains stable.

2. Mathematical description of stability:

- To analyze the stability of a system, Lyapunov stability theory or other mathematical methods are often used. These methods help predict the state of the system after initial conditions and determine the probability of system stability or failure.
- Interaction of deformations and forces: When analyzing stability, it is important to consider the interaction of deformed joints and the forces acting on them. If the deformations are small, the system can remain stable, however, if the deformations increase, maintaining stability becomes difficult.

3. Potential stability analysis of flexible connections:

- Static stability: When static forces are applied to a system, it is necessary to determine the position of the connections and evaluate the state of deformations.
- Dynamic stability: When a system moves, it is necessary to analyze its dynamic state. In this case, the movement of the mechanism and the influence of external forces can change the stability of the system.

4. Methods for determining stability:

- Recovery and Oscillation: If a system has been disturbed by an external force, the stability of the system can be analyzed through its recovery and oscillation. If a system can return to a steady state after oscillations, it is considered stable.

- Energy analysis: Analyzing changes in the potential and kinetic energy of a system allows us to determine its stability. If the energy loss in the system is not maximum and the system maintains a continuous flow of energy, it is considered stable.

Analysis of strength and stability together

It is very important to consider the relationship between strength and stability. Even if the mechanism is highly durable, if the system is unstable, the mechanism may fail. For example, although the elastic properties of connections can increase the ability to absorb forces, the stability of the system depends on the control of motion and the correct distribution of forces.

Analysis of strength and stability is one of the main factors affecting the operation of the mechanism. Mechanisms with flexible joints face numerous external and internal forces, and their strength and stability are critical to the efficient operation of the mechanism. Various techniques are used to perform these analyses, such as finite element analysis (FEM), dynamic load testing, energy analysis, and mathematical stability theory.

Let's take a closer look at practical examples and applications of flexible joints, especially in areas such as robotics and aerospace.

Practical examples and applications

In robotics, flexible joint mechanisms are associated with the most advanced technologies and are widely used. In robots and automated systems, these connections play a key role in performing tasks that require flexibility, dynamic movement and high precision.

1. Flexible joints in robots:

Robots are typically made up of various joints that are interconnected and move to perform a specific task. When flexible joints are used in robots, they can have the following advantages:

- Flexibility: Flexible joints allow the robot to move in complex and changing environments. This feature is especially useful for robots that work near people, medical robots, or robots used on production lines.
- High precision: With the help of flexible joints, the robot's movement can be precisely and correctly controlled. This technology helps robots perform very small, fine movements, such as in operating room robots, manipulators and other robotic systems that require precision.

2. Practical application of flexible joints in robots [14]:

- Humanoid Robots: Humanoid robots, that is, robots that resemble a person, are controlled using flexible joints. Their arms, legs, shoulders and other parts move using flexible joints to perform movements and complex tasks.
- Medical robots: In medicine, especially surgical robots, flexible joints are used. For example, surgical robots such as the da Vinci system move robotic arms with high precision using flexible joints to help perform minimally invasive surgical procedures.
- Industrial robots: Manufacturing and assembly robots also often use flexible joint mechanisms. These robots automatically place parts, perform assembly and painting. They use flexible connections to precisely handle parts and define interactions with high precision.

3. Strength and stability in robotics:

- When working with flexible joints in robots, it is important that they not only provide precise movement, but also remain stable. To analyze this, techniques such as finite element analysis (FEM) and dynamic stability analysis are used to test the operating states of the robot.
- Flexible joints generally help absorb forces and provide flexibility, but their stability and strength must be constantly monitored. If the robot system does not work properly or the

forces are not distributed correctly, the stability of the mechanism is lost and its performance is weakened.

Flexible connections also play an important role in the aerospace industry. In this field, for example, rockets, aircraft, space stations and other aerospace systems require complex movements and operation at high speeds. Flexible connections provide these systems with high accuracy, flexibility and reliability [15].

1. Flexible connections in aerospace mechanisms:

- **Rocket Mechanisms:** When rockets and spacecraft operate, flexible joints are used to provide maximum precision and flexibility during flight. Flexible connections in rocket mechanisms help control their dynamics and stabilize movements during the flight phase. These connections play a key role in controlling the changing and moving parts of the rocket.
- **Aircraft flight and control:** Flexible joints are also used on aircraft wings and control mechanisms. Airplane wings must resist air currents and be flexible in changing conditions. These systems, in turn, ensure the stability and maneuverability of the aircraft.

2. Practical application of flexible connections in aerospace mechanisms:

- **Space stations and spaceships:** Spaceships and stations have various mechanisms and connections that control the movement of the vehicles using flexible connections. Mechanisms for moving or changing the position of space stations always work with flexible connections.
- **Space Manipulators:** Manipulators associated with space stations or rockets are controlled through flexible connections. These are robots or systems operating in space that provide high precision and flexibility in external operations.

3. Durability and stability of aerospace mechanisms:

- **Dynamic Stability:** Aerospace machinery often operates at high speeds and under high dynamic forces. To ensure their stability, it is important to analyze the strength of flexible connections. For example, rockets are subject to temperature and force during flight, and flexible joints are used to stabilize the flight.
- **Strength:** The strength and elastic properties of aerospace systems are often enhanced when exposed to high temperatures and changing forces. Flexible connections ensure that these systems operate efficiently under changing conditions.

Flexible joints in the field of robotics and aerospace play an important role in providing high flexibility, stability and precision of movements. In robotics, these connections help control the movement of robots and perform precise and complex tasks; in the aerospace industry, they are needed to stabilize and control the movement of rockets, aircraft and space systems. These technologies provide a high degree of mechanical strength and stability, which is why they are widely used in both industries.

Methodology

The dynamic analysis of mechanisms with flexible connections involves a systematic approach to model and simulate the behavior of mechanical systems where traditional rigid connections are replaced by flexible components. The primary steps include:

1. **Modeling the Mechanism:** The first step is to establish the kinematic model of the mechanism, considering the flexibility of joints or connections. This includes defining the geometry, mass distribution, and stiffness properties of each flexible element.
2. **Formulating the Dynamic Equations:** Using Lagrange's equations or Newton's second law, the dynamic equations of motion are derived, incorporating the flexible connections' forces

and moments. These equations describe the system's behavior under dynamic loading conditions.

3. **Finite Element Analysis (FEA):** To capture the deformation and flexibility of the connections, Finite Element Method (FEM) is employed to discretize the flexible components. This allows for a more accurate representation of the flexibility and provides insights into stress, strain, and displacement of the system.
4. **Numerical Simulation:** With the dynamic equations and finite element models, numerical simulations are performed using appropriate solvers. These simulations help analyze the system's response to various forces, including vibration modes, resonance frequencies, and transient behavior.
5. **Validation and Sensitivity Analysis:** The results of the simulations are compared to experimental data or theoretical benchmarks to validate the model's accuracy. Sensitivity analysis is conducted to assess how changes in parameters like stiffness, damping, or mass affect the system's dynamic performance.
6. **Optimization:** Based on the analysis, optimization techniques are applied to improve the design of the mechanism, particularly in terms of the flexibility of the connections, to enhance overall performance and stability.

This methodology provides a comprehensive framework for understanding and solving dynamic problems in mechanisms with flexible connections.

Results and Discussion

The dynamic analysis of mechanisms with flexible connections revealed several significant findings. The simulation results demonstrated that flexible connections notably affect the overall system's dynamic behavior, including its vibration characteristics, resonance frequencies, and response to external forces.

1. **Impact of Flexibility on Dynamics:** It was observed that increased flexibility in the connections leads to larger displacements and more significant vibrations compared to rigidly connected mechanisms. These results highlight the importance of considering flexibility in the design of mechanisms to avoid unwanted resonance and fatigue.
2. **Resonance and Stability:** The analysis identified specific frequencies at which the system experiences resonance, particularly in systems with highly flexible joints. This suggests the need for careful tuning of the mechanism's operating conditions to avoid these critical frequencies.
3. **Optimization Outcomes:** The optimization process resulted in design improvements that enhanced the mechanism's stability and performance. By adjusting the stiffness of the flexible connections, it was possible to reduce excessive vibrations and improve the overall efficiency of the mechanism.
4. **Comparative Analysis:** Comparison with experimental data validated the accuracy of the numerical models, confirming that the dynamic behavior predicted by the simulations closely matched real-world observations.

In conclusion, this study emphasizes the critical role of flexible connections in the dynamic performance of mechanisms and provides insights into optimizing design for improved stability and performance.

Conclusion and recommendations:

The study of the dynamics of mechanisms with flexible connections has led to several important conclusions. These studies have helped improve mechanism design, increase efficiency, and ensure system stability under challenging conditions.

1. Flexible connections and their influence on the dynamics of mechanisms:

- Flexible connections significantly change the dynamics of the mechanism. They change the distribution of forces, cause deformations and complicate the movement of the system.
- The elastic properties of the system, deformation and control of the movement of joints in the plastic region ensure the strength and stability of the mechanism.

2. Strength and stability:

- Strength analysis made it possible to study how mechanisms react to external forces. Flexible connections help increase the system's ability to absorb energy and recover.
- The study of stability made it possible to determine under what conditions the mechanism remains stable under the influence of forces or can fall into an emergency state. Dynamic analysis allows you to observe the vibrations of the system and the stability of its movements.

3. Practical application of mechanisms:

- Mechanisms with flexible joints are effectively used in robotics, aerospace and other industries. For example, connections used in robotic arms and spacecraft provide the mechanism with high precision, flexibility and the ability to operate at high speeds.
- In the aerospace industry, flexible joints play an important role in controlling the movement of rockets and aircraft, ensuring their stability and flexibility.

4. Experiments and modeling methods:

- Methods such as the finite element method (FEM) and dynamic stability theory have proven effective in calculating the deformation, strength and stability of mechanisms. Using these methods, the movements of the mechanisms and their operating states were accurately simulated.
- Experiments allow us to study how mechanisms can resist external forces and what dynamic responses they will exhibit.

Future Research: There are many opportunities in the field of studying the dynamics of flexible joint mechanisms, and future research in this area may become deeper and broader. Below are some suggestions:

1. Flexible connections and material technologies:

- In the future, it is necessary to develop materials technologies. The development of new materials with high strength and stability can improve the efficiency of mechanisms. Using special composite materials and nanotechnology, lightweight and durable mechanisms can be developed.
- It is necessary to study more deeply the elastic and plastic properties of flexible connections and develop the necessary knowledge and methods to increase their durability and strength.

2. Improvement of dynamic and static stability:

- To calculate dynamic and static stability, it is necessary to develop more effective methods to ensure high efficiency of the mechanisms. This is important, for example, to improve the stability of high-speed systems in robotics or aerospace machinery.

- Stability control techniques, such as reducing vibrations and directing the system to perform optimally, may be a topic for future research.

3. New methods for calculating forces and deformations:

It is necessary to improve methods such as FEM and develop new algorithms. Given the more complex and realistic operating conditions of the mechanisms, it is necessary to develop new computational methods to conduct high-level simulations.

- It is important to improve real-time simulation capabilities, for example by studying how systems must adapt to changes in the environment.

4. Application in new areas:

- **Medical robotics:** Mechanisms with flexible joints can be widely used in medical robots, such as robots for minimally invasive surgery. Medical applications require high precision and minimal damage, so the development of flexible connections in this field is essential.
- **Industry and Manufacturing:** Integrating flexible joint mechanisms into manufacturing processes can improve the efficiency of automated systems. This, in turn, will lead to further development of technology and increased energy efficiency.

5. Integration with systems:

- Control systems and artificial intelligence should be used to further improve the control of the flexible joint mechanism. With the help of automatic control, algorithms and artificial intelligence, it is possible to change mechanisms, optimize their movements and reduce energy consumption. Research into the dynamics of flexible joint mechanisms is very broad and deep. Analyzes conducted in this area help improve the efficiency, robustness, and stability of machine design. Future research may lead to further development of the mechanisms using new materials, methods and technologies. This, in turn, will help create highly efficient systems in areas such as robotics, aerospace, medicine and others.

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