

# Dynamic Analysis of Multi-Degree-of-Freedom Mooring Mechanisms

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**Abstract.** This paper analyzes the bottleneck issues in automatic ship mooring technology and highlights the importance of dynamic analysis in mooring mechanism design. Subsequently, dynamics modeling and simulation were conducted for a mooring mechanism capable of pitching, telescoping, and rotating. Key parameters such as force, angular velocity, angular acceleration, and torque at critical joints were extracted. The obtained results were thoroughly analyzed to evaluate the dynamic performance of the mechanism.

**Keywords:** dynamic analysis, MDOF, mooring

## 1. Introduction

Automatic ship mooring represents a critical next-phase component in the digital transformation of ports and shipping. It is a disruptive technological innovation capable of enhancing overall terminal operational efficiency and eliminating casualties during operations[1]. While automated mooring technology has achieved maturity abroad, it remains monopolized by a handful of suppliers. Conducting research on key technologies of automatic mooring is therefore essential: it meets the current demand for reducing costs, improving quality, and increasing efficiency in port operations; it supports the development of smart transportation infrastructure; it addresses the risk of critical technology being restricted by external suppliers; and it contributes to achieving high-level scientific and technological self-reliance[2].

The core mechanisms of an automatic mooring system consist mainly of two parts: the adsorption mechanism and the main actuating mechanism. Due to the multi-joint, multi-degree-of-freedom kinematic characteristics during the adsorption process, the main actuator can be regarded as a multi-degree-of-freedom robotic arm. Furthermore, given the complex composition of external loads it bears, and the substantial and complicated kinetic, potential, and inertial energies of the target vessel, its kinematic and dynamic behaviors are highly complex.

Dynamic research is an indispensable part of the development process of robotic and robotic-arm mechanisms. It plays a crucial role in evaluating the performance of such systems and improving their control accuracy. Dynamic analysis primarily aims to provide theoretical support for mechanisms still in development or to optimize parameters of existing products for quality enhancement. Without a clear understanding of the dynamic processes of the main actuating mechanism in automatic mooring systems, it is difficult to achieve an optimal technical solution at the mechanical design level.

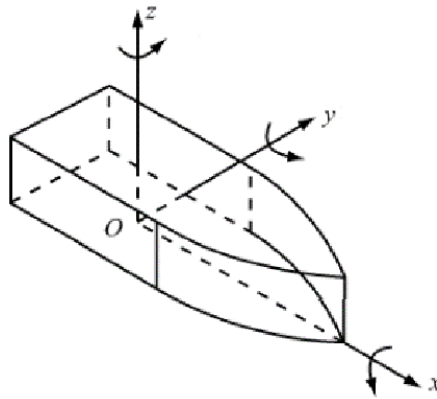
This paper takes this as its starting point. Utilizing kinematic and dynamic theories, it proposes an optimized form of the main actuating mechanism for automatic mooring devices, thereby providing important theoretical support and technical solutions for the overall optimized design of multi-degree-of-freedom mooring units.

## 2. Analysis of Mooring Object Motion States

First, preliminary foundational conditions for the project research are established. During the automatic mooring process, the forces acting on the ship are complex, resulting in highly intricate composite motions across three planes: surge, sway, and heave, as well as rotations about three axes: roll, pitch, and yaw. Therefore, it is essential to begin by analyzing the ship's motion behavior during mooring to clarify the overall state of the object acted upon by the automatic mooring system.

Simultaneously, the complex coupled force field of external loads borne by the automatic mooring device must be analyzed to define the preliminary foundational conditions of the project, including boundary conditions and load conditions.

Mooring analysis of ships involves calculating the motion range and force conditions of a vessel in a moored state. Under the influence of external environmental factors such as wind, waves, and current[3], the motion response and forces on a moored ship become highly complex. The motion state can be decomposed into six degrees of freedom: three linear movements—lateral motion (away from or toward the dock), longitudinal motion (forward or backward), and vertical motion (up and down)—and three rotational movements—rolling, pitching, and yawing, as shown in Fig. 1. Due to the randomness of external loads such as waves, the most critical scenario occurs when loads superimpose in the same direction. In this case, the ship's motion exhibits three independent modes: roll, sway, and heave.



**Figure 1.** Mooring Object Motion States

### 3. Kinematic Analysis

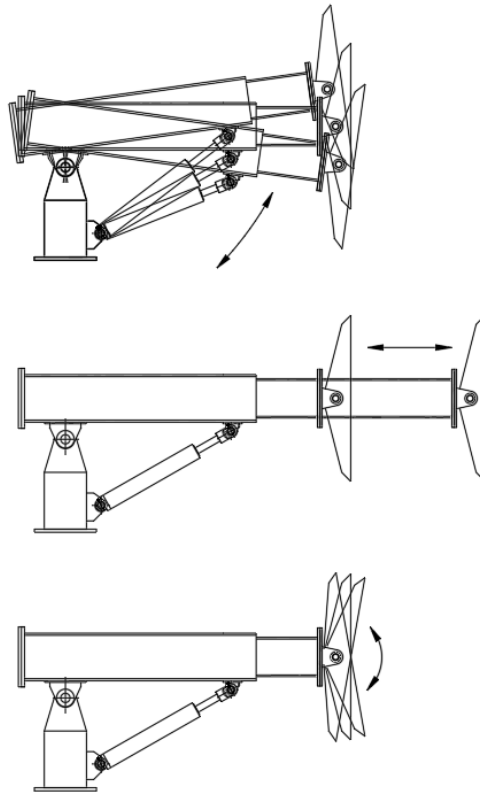
Based on kinematic theory, and the mathematical relationship between the terminal motion state of the mooring mechanism and the variables of each degree of freedom, a kinematic description of the multi-degree-of-freedom mooring mechanism is established. This study investigates coordinate transformations under complex motion conditions, derives kinematic equations, and analyzes the workspace and end-effector pose of the mechanism. The posture, motion trajectory, and workspace are visualized graphically. Building on this analysis, the performance of the multi-degree-of-freedom mooring mechanism is further evaluated, laying a theoretical foundation for enhancing the reliability and advancement of the design.

Mechanical kinematics is one of the primary research areas in robotics, focusing on the spatial description of mechanisms to determine motion parameters and understand their motion characteristics in working environments, without involving mechanical theories[4]. By establishing positional descriptions of the mechanism, the positional relationships among its components are obtained, ultimately defining the correspondence between the end-effector and joint variables. Kinematics concerns changes in spatial position and the resulting displacements, as well as other motion parameters derived through differentiation with respect to time—all of which fall within the scope of kinematics. In kinematic research, inverse kinematics is particularly challenging due to its nonlinear nature. The study of mechanism kinematics essentially involves constructing a mathematical model of the mechanism's spatial geometry, using matrices to represent positional relationships and other kinematic parameters, thereby providing references for practical applications and performance evaluation.

Robotic arm kinematics describes and studies the motion characteristics of the arm from a geometric or structural perspective, without considering force interactions. Kinematic simulation of robotic arms is a crucial component of robotics technology. Visualizing the posture, motion trajectory,

and workspace of the robotic arm graphically facilitates the study of its performance and contributes to improving the reliability of robotic arm design.

The initial mechanism design adopts a non-eccentric configuration for the main pitch rotation center, with the pitch hinge point positioned at the lower section of the telescopic arm, as illustrated in Fig. 2. During kinematic analysis, the hinge point location is iteratively adjusted for optimization—for instance, by configuring the main pitch rotation center as eccentric and relocating the pitch hinge point to the upper section of the telescopic arm.



**Figure 2.** Initial Mechanism Design

Regarding the kinematic description of robotic arms, in the mid-20th century, Denavit and Hartenberg proposed a method known as the D-H method. This approach assigns a single variable to the spatial transformation between adjacent link coordinate systems, using matrices to spatially represent the position and orientation of links. By employing homogeneous matrices to express the kinematic relationships of spatial mechanisms, it converts spatial pose relationships into matrix solutions. The method derives the pose transformation from adjacent linkages to the end-effector relative to the base, ultimately completing the establishment of the robotic arm's kinematic relationship model.

#### **4. Methods of Dynamics Research**

Robotic arm dynamics focuses on analyzing the relationship between the motion of the robotic arm and the driving forces behind that motion. Specifically, it establishes the relationship between the joint motion parameters of the robotic arm and the joint driving forces or torques. The foundation for achieving this goal lies in the dynamic modeling of the robotic arm. For the analysis and study of robotic arm dynamics, the following commonly used solution methods are currently employed[5].

The Newton-Euler equations are based on Newton's and Euler's equations, establishing the motion relationships of the connecting rod's center of mass. By treating the connecting rod as a rigid body, motion is induced by imparting acceleration to it. There is a corresponding relationship between the

force required for the connecting rod's motion and its desired acceleration, as well as the mass distribution of the connecting rod.

This relationship is then generalized into a mathematical model of robotic arm dynamics. The Newton-Euler method involves steps such as outward iteration and inward iteration, ultimately calculating the motion parameters of the connecting rods and the combined external and internal forces acting on them to determine the joint torques of the robotic arm.

Kane's equation method is commonly used for dynamic modeling of robotic arms. This method primarily utilizes generalized speeds as independent variables for dynamic modeling. When applied to robotic arms with complex structures, it can reduce cumbersome calculations. It has a wide range of applications, can be combined with the finite element method, and is also capable of solving non-holonomic system problems.

For robots with complex spatial structures, the constraints are also intricate, making the establishment of dynamic differential equations challenging. In such cases, the advantages of modeling based on Gauss's principle become apparent. Its mathematical form is unified and does not change with constraints. Gauss's principle employs variational methods for numerical calculations, using system acceleration as a variable and treating the motion that minimizes the constraint function as the true motion. This transforms mechanical problems into mathematical models by altering the required variables. It can also be used for dynamics research based on optimization criteria.

## 5. Dynamics Modeling

Dynamics is the theory that studies the relationship between the motion of structures and the forces applied. Mechanism dynamics primarily involves two research directions: forward and inverse dynamics. The forward dynamics problem deduces the motion parameters of joints from driving forces, while inverse dynamics calculates the required joint torques based on known system states. This can be applied to determine optimal energy consumption modes of mechanisms and the selection of driving components.

The analysis of mechanism dynamics is grounded in dynamic computational models, supplemented by computer-based simulation experiments. By solving dynamic models, the dynamic characteristics of mechanical systems can be obtained and their parameters evaluated, providing valuable applications for mechanism improvement and quality enhancement.

ADAMS, developed by the American company MDI, is a widely favored analysis software in the field of robotics simulation. Based on the Lagrangian method for mechanism simulation, it enables users to conveniently build virtual prototypes for kinematic and dynamic simulation analysis. The corresponding motion and force curves can be obtained in the post-processing module.

Within the ADAMS user interface, the first step is to configure the working environment. Then, imported model parts are reorganized and constraints are applied. Drive functions are input at the joints, along with external applied loads. Finally, the simulation step size and duration are set. After the calculation is completed, an animation of the analysis process can be generated, and simulation data acquisition is completed[6].

When establishing dynamic models and performing simulations, describing motion relationships and applying loads often involve the use of functions. During simulation analysis, it is frequently necessary to import or export data files in the software. Spline functions are commonly used to process such data. A spline function is a type of numerical curve that fits data imported into data units to form data curves. The ADAMS/View module provides three types of spline functions based on different fitting methods: CUBSPL, AKISPL, and CURVE.

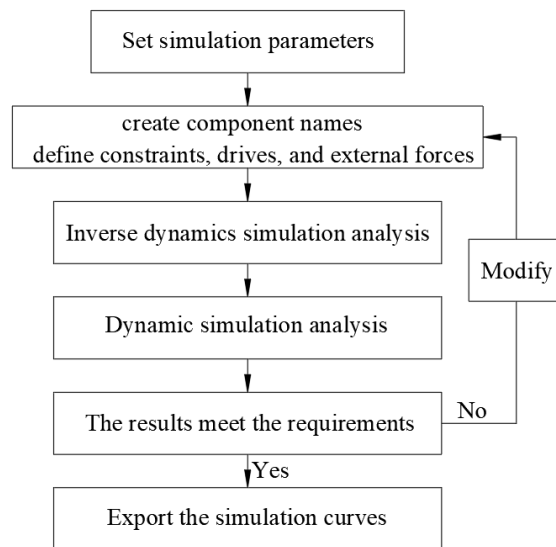
The AKISPL function uses the Akima method for differential calculation of spline data. It employs local fitting, resulting in fast interpolation speed, and each point on the curve only affects neighboring points. The curve fitted by this method is relatively smooth.

The CUBSPL function adopts a cubic spline curve fitting approach. Any local modification can affect the shape of the curve; moving a single point causes the entire curve to change. The first and

second derivatives of the CUBSPL function are continuous, ensuring convergence regardless of whether the spatial points are uniformly distributed.

The CURVE function uses B-spline curve fitting, typically employed for fitting spatial curves. When establishing relative motion relationships and force interactions between components, the CUBSPL and AKISPL functions are generally used for curve fitting.

First, the 3D modeling software SOLIDWORKS was used to create a three-dimensional model of the mooring robotic arm. The model was then converted and imported into ADAMS simulation software. Next, material properties of components were defined, constraints were added, and motion and load data from hydrodynamic analysis were imported into data elements as driving conditions. Finally, the entire system was simulated. The workflow for establishing the virtual prototype is shown in Fig. 3.

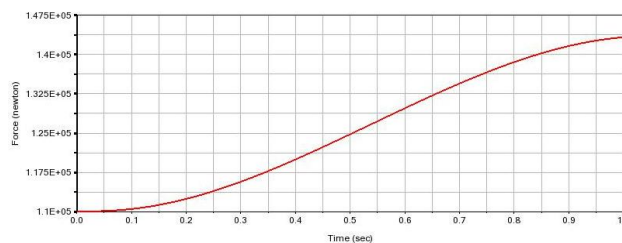


**Figure 3.** The workflow for establishing the virtual prototype

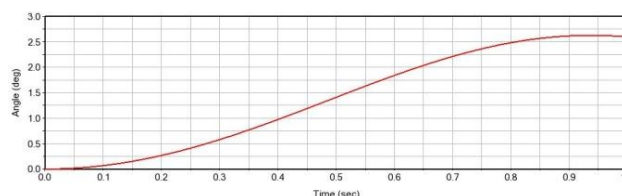
During the model construction process, it is necessary to define rigid bodies, kinematic pairs, and external forces, while also applying dampers. Parameter modifications are implemented using the STEP function, formulated as STEP(initial time, initial parameter, final time, final parameter).

## 6. Post-Processing of Dynamic Simulation Data

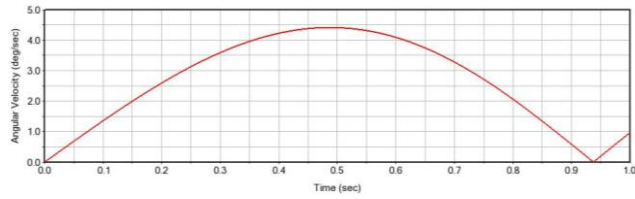
The force, rotation angle, angular velocity, angular acceleration, and torque of the shoulder and wrist joints in the mooring mechanism are shown in Fig. 4.



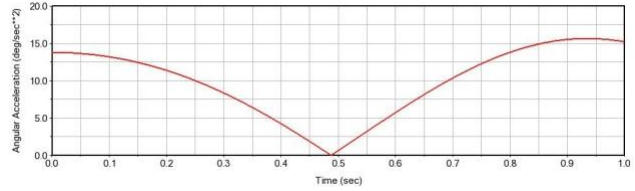
a) Shoulder joint force



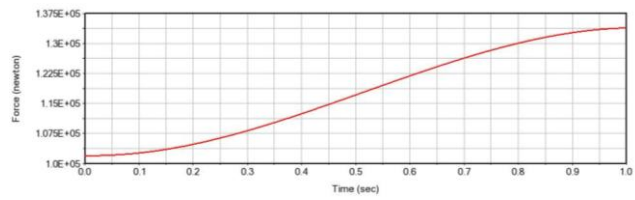
b) Shoulder joint rotation angle



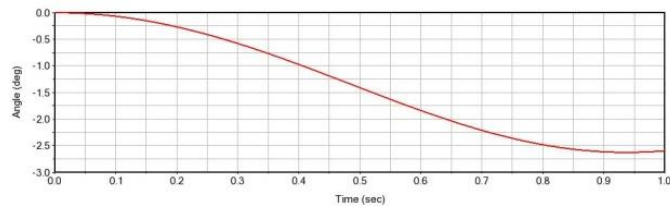
c) Shoulder joint angular velocity



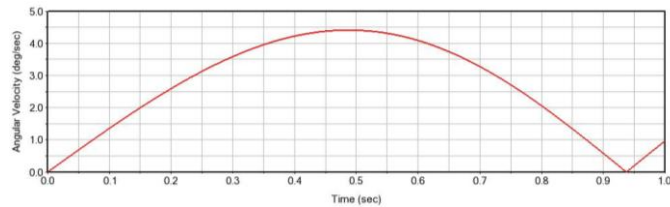
d) Shoulder joint angular acceleration



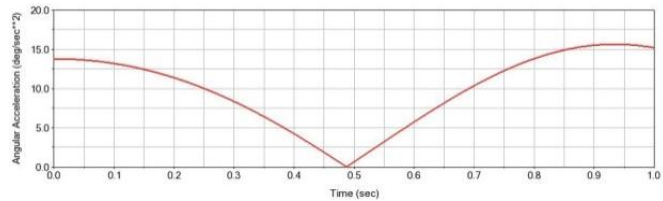
e) Wrist joint force



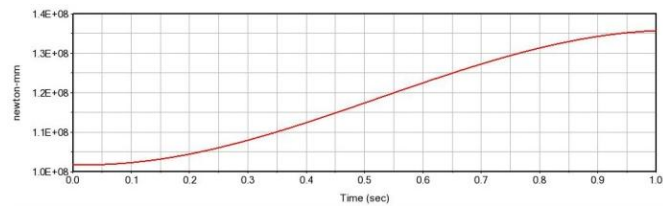
f) Wrist joint rotation angle



g) Wrist joint relative angular velocity



h) Wrist joint relative angular acceleration



i) Joint torque

**Figure 4.** Dynamic simulation data

Based on the results, it can be concluded that the degree-of-freedom design of this mechanism is reasonable, with an appropriate number of constraints, complying with the principles of mechanism theory. Analysis of the displacement and trajectory of key points (such as the end-effector and joints) demonstrates that the mechanism can successfully reach all intended working positions.

This study plots the velocity and acceleration curves of the joints and sliding pairs. Acceleration is directly related to inertial forces and torques, forming the basis for dynamic analysis and structural stress evaluation. The joint acceleration curves indicate that high peak accelerations imply significant inertial impact, vibration, and noise, which are critical indicators for assessing mechanism performance. The proposed design exhibits smooth acceleration curves with low peak values, reflecting an optimized mechanical design. No "dead points" or "unstable points" are observed within the workspace.

## 7. Research Outlook

Further investigations could be conducted in the following areas.

When mooring large vessels, the coordinated operation of multiple mooring robotic arms may be required. This application scenario warrants further investigation in future studies.

Additional damping adjustment tests should be incorporated.

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