**Nonlinear Dynamics in Crane Ship Motion**

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# 1 Introduction

Floating cranes are applied for a variety of tasks in marine technology. Practical problems arise during crane ship operations due to difficulties in positioning the objects being handled accurately, which could result in collisions. Weather sensitivity of the vessel's motion causes high amplitude motion of the crane and the load, that has to be avoided since the allowable range of acceleration of the crane tip is limited.

Because of the importance of crane ship operations – especially during the assembly of costly structures such as drilling platforms – it is necessary to determine critical ranges of operating conditions.

In coastal regions crane barges are common for lift operations; in offshore engineering, the larger crane ships or semisubmersibles can be found. All are used for transportation, the construction of large offshore structures and for salvage operations.

The aim of a cooperative research project is to get a mathematical description for crane ship operations which enables predictions about the dynamical behavior of the complete system. Then the results of the analysis can be used for safety considerations and to enlargen the operating range of crane ships by means of active damping devices.

In this paper we will investigate the dynamics of a crane vessel periodically excited by regular waves. We start with a description of the experimental and numerical techniques used to determine multiple attractors and to create bifurcation diagrams. Then we will present a comparison between the results and give an overview about different passive and active damping devices which are being investigated.

Different approaches for investigating the dynamics of crane vessels were used in recent years: Rieckert [11] applied a linearized mathematical model with eight degrees of freedom to obtain transfer functions which were then compared to experimental results. The influence of nonlinearities arising from the mooring system and viscosity effects of the fluid are included in a model developed by Jiang and Schellin [6]. The same model was used in a similar study by Kral et al. [7]. They also showed that different phenomena, from period doubling to chaos, can be found in the dynamics of a crane vessel.

# 2 Experiments

The experiments considered here were made with models of different crane vessels. At the Technical University Hamburg-Harburg a crane barge scaled 1:100 was investigated, at the Berlin University of Technology a crane barge scaled 1:25, a crane ship and a semi-submersible both scaled 1:75 were used for the experiments.

## 2.1 Experimental setup

The experimental setup consists of a moored crane vessel which is excited by sinusoidal waves in a wave tank.

The model crane vessel consists of two main components which can be considered as rigid bodies: The hull of the vessel with the crane attached and the load. The load is represented by a pendulum which is pivoted at the crane tip. Different sensors allow for a determination of the position of the hull, its orientation and the angle of the pendulum relative to the crane.

In different numerical calculations cartenary mooring systems have revealed a highly nonlinear relation between the displacement of the moored vessel and the restoring force. It was found that it is difficult to obtain similar characteristics experimentally. Therefore, a spring mechanism was developed to correctly simulate mooring line forces as described by the mathematical model (see also Ellermann [3]). This mechanism consists of a spring and a combination of a cam and a roll yielding a non-uniform ratio between the surge motion of the vessel and the strain of the spring.

### 2.2 Nonlinear phenomena in experimental results

During the experiments the moored crane vessel was excited by regular waves. It was shown, that nonlinear phenomena – such as period doubling and multiple attractors – existed within the operating range of the vessel. For the small scale model (1:100) the transient behavior after disturbances in the state of the system was not a major concern, since they decayed rapidly – usually in less than a minute, for larger models this time was considerably longer. Measurements were taken after the steady state has been reached.

The motion which was found experimentally can be classified as period-one (P-1), period-two (P-2) or period-three (P-3). In some cases coexisting attractors were found by disturbing the system. This was usually done by prescribing high initial strain forces in the mooring system, i.e. by setting the initial position $x_o \neq 0$.

By varying one of the system's parameters – in this case the length of the hoisting rope – bifurcation diagrams were obtained experimentally.

## 3 Numerical investigation

The numerical investigations were done in parallel to the experiments. The mathematical model used for the calculations is based on the work of Jiang [5] and is described by Ellermann and Kreuzer [4]: The equations of the system can be written as

$$\mathbf{M}(\mathbf{y})\ddot{\mathbf{y}} + \mathbf{k}(\mathbf{y}, \dot{\mathbf{y}}) = \mathbf{q}(\mathbf{y}, \dot{\mathbf{y}}) \tag{1}$$

with the inertia matrix $\mathbf{M}$, the generalized applied gyroscopic forces $\mathbf{k}$, the generalized forces $\mathbf{q}$ and the vector of generalized coordinates $\mathbf{y} = (x,\ \theta,\ z,\ \alpha)^T$ describing the surge-, pitch- and heave-motion of the hull and the angle between the crane boom and the load. The vector $\mathbf{q}$ includes

- hydrostatic forces,
- mooring-line forces,

- viscous drag,
- exciting wave forces, and
- the linear hydrodynamic response forces.

The hydrodynamic response forces are calculated from a finite state space model: This model, which is described in detail by Jiang [5], is based on the assumption that the amplitudes of the waves and the rigid body motion are small so that superposition can be applied. The frequency dependent terms of added mass and added damping, calculated from potential theory, were transformed into time domain.

These considerations lead to a set of twenty differential equations for planar motion of the vessel, including the rigid body motion given in (1) and the state space model.

## 3.1 Simulation

The use of the mathematical model for numerical simulation is straight forward: Results are easily obtained by the integration of the equations of motion. Here the simulations are mainly used to eludicate the type of motion.

## 3.2 Bifurcation analysis

Since numerical simulation is time consuming and the results only characterize the motion for specific positions in state space, bifurcation analysis was used to analyze the system. The analysis focuses on periodic solutions characterized by an algebraic equation of the form

$$\mathbf{G}(\mathbf{x}) = \mathbf{P}^{l}(\mathbf{x}) - \mathbf{x} = 0 \tag{2}$$

where $P$ means the Poincaré-map of $\mathbf{x}$, $l$ is the periodicity of the motion.

In order to obtain a bifurcation diagram one of the system's parameters is varied quasi-statically whereas the other parameters are kept constant. The software which was used for the bifurcation analysis applies path following algorithms to trace stable or unstable periodic motions, see Baumgarten [1]. Different solutions are approximated by a set of points, showing the evolution of the solution as the parameter changes.

A change of stability between two consecutive points indicates a bifurcation. For the analysis of the crane vessel this could mean that a new branch with a different periodic behavior is emerging between those two points, but it could also result in chaotic motion. To find different solutions near bifurcation points, the state of the system was disturbed so that the initial state was in the bassin of attraction of a different attractor. Shooting methods were then applied to find a new starting point for the path following algorithm on the bifurcating branch.

The current implementation of the mathematical model allows for bifurcation analysis with different parameters: Earlier investigations mainly used the length of the hoisting rope as parameter (see Ellermann and Kreuzer [4]). Here also parameters describing the mooring system ($c_1$ and $c_3$) and the amplitude of the exciting wave were used as varying parameters.

# 4 Comparison of numerical and experimental results

One aim of this paper is to describe a mathematical model for a crane barge which allows for predictions of the motion and a determination of insecure operating regions. The numerical results for the mathematical model of the crane barge of the Berlin University of Technology are shown in Figures 1 to 3. The figures present the bifurcation diagrams for the surge motion of the barge; the Poincaré-map was determined for the phase angle zero, hence, at $t = 0$ within the period of forcing.

The graphs were obtained with the same forcing frequency. They show a period-one motion which is stable for a wide range of parameters. Different solutions are coexisting: In Figure 1 it can be seen that a variation in the length $l$ of the hoisting rope can lead to a sequence of period-doubling bifurcations. In addition to the P-1 and P-3 motion which are stable for small values of $l$, periodic motions with the period two, four, six or eight were found for larger values of $l$.

When considering the parameters $c_1$ and $c_3$ of the mooring system, P-2 and P-3 motion are found for soft mooring systems: For the parameters used in Figure 2, a stable motion with period three exists up to a critical value of $c_1 = 80 kN/m$, while the P-2 motion remains up to $c_1 = 195 kN/m$.

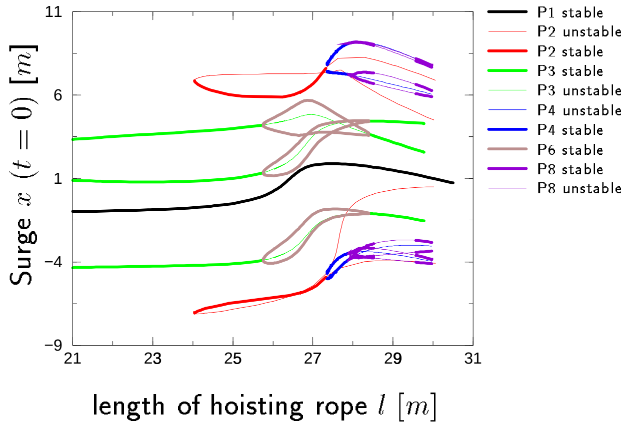



Figure 1: Numerical bifurcation diagram

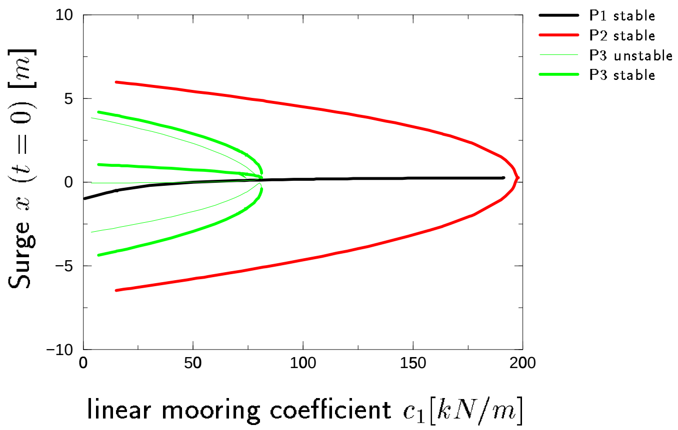



Figure 2: Numerical bifurcation diagram

This is in good accordance with experimental results: Clauss and Vannahme [2] experimentally determined P-3 motion with soft mooring mechanisms and P-2 motion for a setup with a stiff mooring line force.

Figure 3 shows that for the mathematical model P-3 motion was found even for small values of the coefficient $c_3$, but it has to be noted that the amplitude of the motion is very high and would reach the limits of the physical model. This could result in a failure of the mooring system.

In Figure 4 the motion of the vessel is shown by the means of phase diagrams with Poincaré-points marking the state of the system with respect to the period of the forcing wave. It has to be noted that the changes which occur at a period-doubling (e.g. from period two to four) bifurcation are compara-

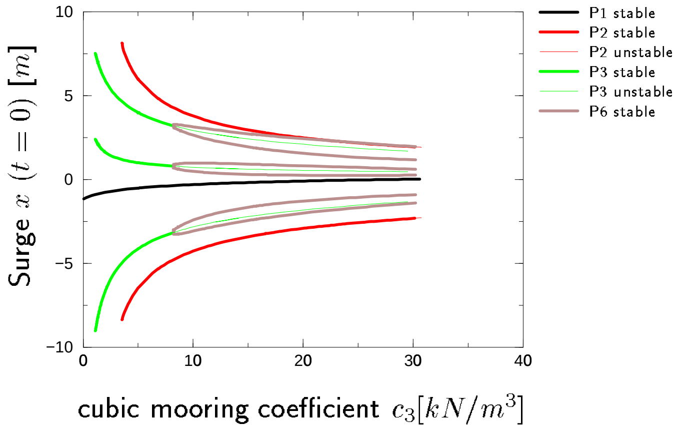



Figure 3: Numerical bifurcation diagram

tively small: They can easily be seen from simulations but experimental data always includes a certain amount of noise and disturbances which make it difficult to detect these differences.

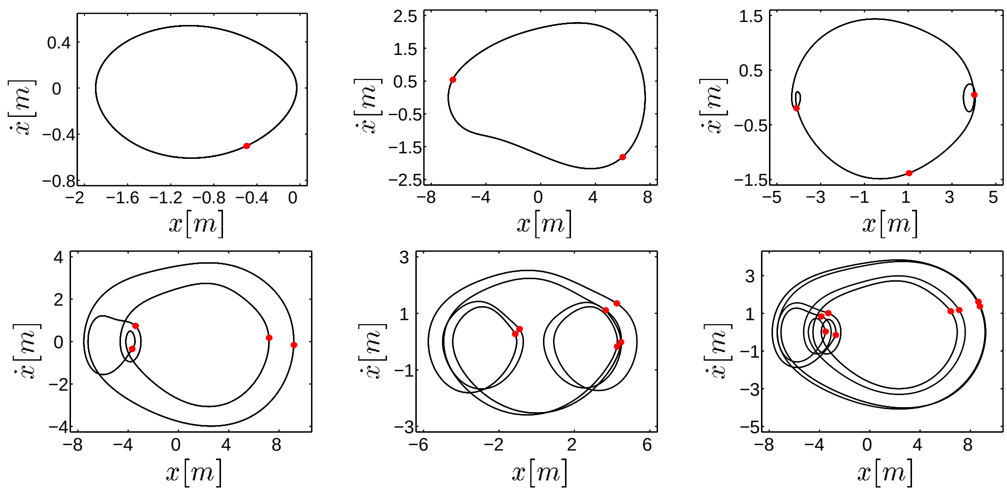
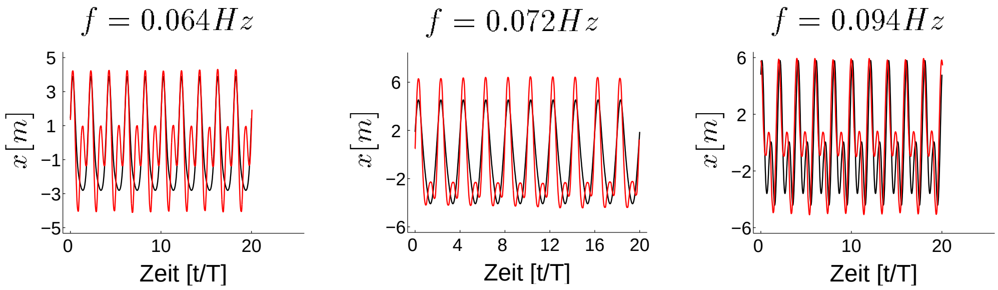


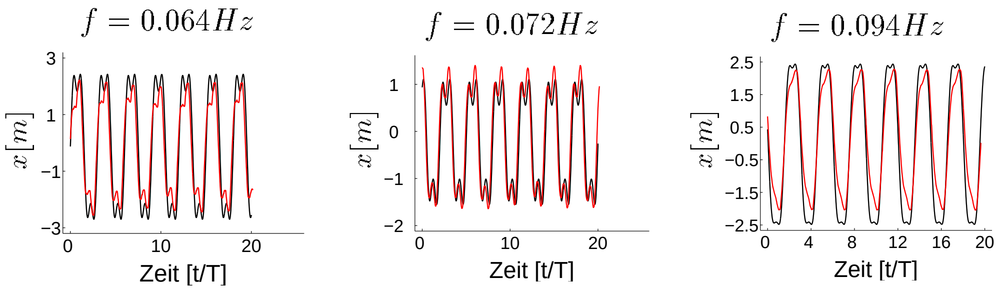

Figure 4: Phase diagrams for periodic surge motion

It has to be noted that experiments in which different paths of a bifurcation diagram are to be determined with only small steps between the discrete points, are very time consuming. Therefore, the comparison between the numerical and the experimental results include some discrete points rather than entire paths.




—— experimental results
—— numerical results

Figure 5: Comparison of results — P2 – solutions




—— experimental results
—— numerical results

Figure 6: Comparison of results — P3 – solutions

The results for different frequencies with P2- and P3-motion are shown in Figures 5 and 6: For all the frequencies given in these examples stable attractors with the corresponding types of motion exist in the numerical as well as the experimental model. Even though the resemblance for the P2-motion is not as good as for the P3-motion, the values for the displacements calculated in the simulation are resonably close to the experimental results.

# 5 Damping devices and active elements

Apart from classifying the type of motion of the vessel one aim in this project is to develop design criteria or mechanisms, including passive and active damping devices, in order to enlargen the operating limits.

In literature different means of active control of the dynamics can be found:

The McDermott Derrick Barge (DB) 50 uses open bottom tanks. These tanks can be pressurized in order to control the waterlevel in the tanks and thus to counteract the motion of the vessel, see Figure 7.

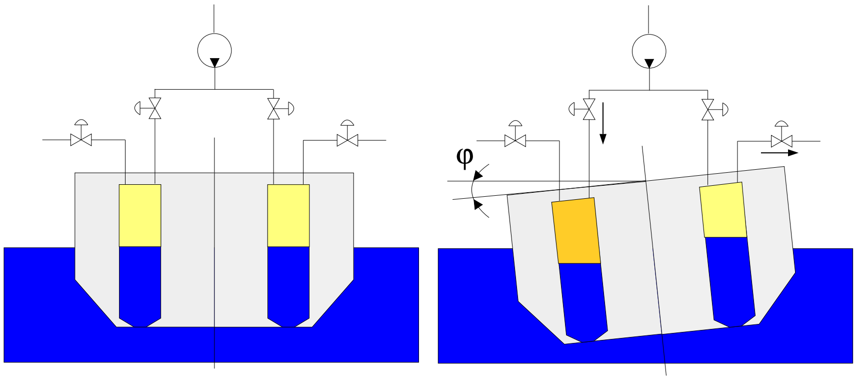



Figure 7: Motion suppression system (DB 50)

A detailed description of this motion suppression system can be found in *The Motorship* [14] or Patel et al. [10].

Yuan et al. [13] consider pulley-brake mechanism with an adjustable friction force. They showed that this device can cause a significant reduction of the load pendulation by changing the system's eigenfrequency.

The approach to be investigated here uses the so-called tugger lines: These ropes connect the load to the hull, which leads to a modified multibody system: The force in the tugger lines can then be used as control parameter, see Figure 8.

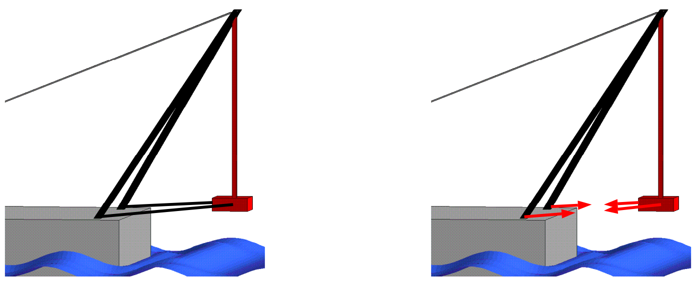


Figure 8: Tugger lines

The force in the ropes can either be considered as damping force or it can be modelled by active elements. Depending on the mechanism which causes the tension of the rope, the corresponding equations are included in the system's equations.

In first tests, different passive and active mechanisms gave promising results for floating cranes with a small ratio between the mass of the payload and the mass of the vessel. Devices based on dry friction or the application of actuators can significantly reduce the motion of the load. The problems that arise with tugger lines are the forces needed to influence the motion of large payloads: In this case the technical realization of any tugger line mechanism would be difficult.

# 6 Conclusions

It was found in the experiments as well as in the numerical investigation that nonlinearities have a significant influence on the dynamics of the crane vessel. Especially the mooring system is critical with respect to the motion of the ship. Due to different nonlinearities the system exhibits phenomena which cannot be described by purely linear models.

As a result of the sensitive dependence on parameters as well as initial conditions, predictions of the system's motion remain difficult, particularly in the vicinity of bifurcation points the numerical results can differ from experimental data. But apart from these regions, numerical data is in good agreement with the experiments.

# 7 Acknowledgments

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