Enhancing damping of gas bearings using linear parameter-varying control

Journal bearings can be lubricated through controllable injectors using pressurised fluids, whose viscosity highly determines the dynamic responses of the rotating machine. The use of fluids with low viscosity is attracting a growing interest due to the reduced friction forces and consequent losses when the machine is in operation. However low viscosity also entails poor damping properties, which may lead to degraded performance or even instability when the rotating machine operates at or near one of the modal frequencies. This issue can be properly addressed by employing active feedback control systems to regulate the injection pressure of the fluid. Due to the strong dependencies of system performance on system parameters, the sought controller should be robust over a large range of operational conditions. This paper addresses the damping enhancement of controllable gas bearings through robust control approaches. Through an extensive experimental campaign the paper evaluates two robust controllers, a linear parameter-varying (LPV) controller and $\infty$ controller, on their capability to guarantee stability and performance of a gas bearing across the large operational envelopes in rotational speed and injection pressure. The control systems are designed applying state-of-the-art methods in the respective areas. The experimental results clearly demonstrate the feasibility of enhancing the damping properties of a gas bearing by means of robust control methods.
Low-complexity Behavioral Model for Predictive Maintenance of Railway Turnouts

Maintenance of railway infrastructures represents a major cost driver for any infrastructure manager since reliability and dependability must be guaranteed at all times. Implementation of predictive maintenance policies relies on the availability of condition monitoring systems able to assess the infrastructure health state. The core of any condition monitoring system is the a-priori knowledge about the process to be monitored, in the form of either mathematical models of different complexity or signal features characterizing the healthy/faulty behavior. This study investigates the identification of a low-complexity behavioral model of a railway turnout capable of capturing the dominant dynamics due to the ballast and railpad components. Measured rail accelerations, acquired through a receptance test carried out on the switch panel of a turnout of the Danish railway network, have been utilized together with the Eigensystem Realization Algorithm – a type of subspace identification – to identify a fourth order model of the infrastructure. The robustness and predictive capability of the low-complexity behavioral model to reproduce track responses under different types of train excitations have been successfully validated. It is anticipated that the identified model will be instrumental for the development of methods for diagnosis and prognosis of faults and degradation process in switches and crossings.
Self-reconfiguration of Modular Underwater Robots using an Energy Heuristic

This paper investigates self-reconfiguration of a modular robotic system, which consists of a cluster of modular vehicles that can attach to each other by a connection mechanism. Thereby, they can form a desired morphology to meet task specific requirements. Reconfiguration can be needed due to limitations from dimensions of passable corridors for an underwater maintenance task, for supplemental instrumentation that is available on a particular robot, or as remedial action if one robot in a cluster suffers from malfunction. Being crucial for autonomous underwater vehicles, energy consumed is employed as a heuristic. The paper shows how the Basic Theta* algorithm can be guided by an energy criterion to calculate a transition from start- to goal morphology. Individual robots are guided while minimizing the overall energy for propulsion and for balancing restoring forces and moments in morphologies. The properties of the proposed self-reconfiguration algorithm are evaluated through simulations and preliminary model tank experiments. The energy based heuristic for reconfiguration is compared to a traditional solution that minimizes the Euclidean distance.

Advanced Control of Active Bearings - Modelling, Design and Experiments

In all rotating machines relative movements between the stationary parts and the rotating parts imply energy loss and, in many critical cases, vibration problems. This energy loss leads to higher overall energy consumption of the system. Research activities towards the reduction of friction, the enhancement of damping, the extension of operating range and the minimisation of critical vibrations in machine elements are of fundamental importance. The main component to tackle the energy-loss-related problems is the bearing. The area of design of active bearings, while very promising, is still in its early development mainly because of its high complexity and its multiphysics nature. The state-of-the-art models derived from first principles and axioms of mechanics are complex and often subject to significant parameter uncertainties. They are challenging to develop and not easily used for feedback control design. One example is the controllable radial gas bearing, where the lubricant air is injected through controllable injectors to levitate the rotor on an air film. Feedback control of the injection can improve upon the poor damping to reduce the disturbance sensitivity and vibrations near the critical speeds. The feedback control law is
preferably designed from a simple model, which captures the dominant dynamics of the machine in the frequency range of interest. This thesis offers two main original contributions in the field of active bearings. First, an experimental technique is proposed for "in situ" identification of low complexity models of the entire rotor-bearing-actuator-sensor system. The approach employs grey-box identification techniques and is easily applied to industrial rotating machinery with controllable bearings. The approach is applied for identification of a linear parameter-varying model of a rotor supported by an active gas bearing. Second, is the application of model-based control techniques for controllable gas bearings. The parameter-varying model is shown to suit the design of classical and modern control including observer and state-feedback, H1, LPV and gain-scheduled H2 control designs to improve upon the dynamic properties of the gas bearing test rig. Experimental results using the control designs show that the controllers can increase the damping significantly. The damping enhancing controllers are shown to extend the range of safe operation by a 70% increase in shaft angular velocity, thereby allowing safe operation in and above the regions of the first and second critical speeds.

Evaluation of Shipboard Wave Estimation Techniques through Model-scale Experiments
The paper continues a study on the wave buoy analogy that uses shipboard measurements to estimate sea states. In the present study, the wave buoy analogy is formulated directly in the time domain and relies only partly on wave-vessel response amplitude operators (RAOs), which is in contrast to all previous works that either are formulated in the frequency domain and/or depend entirely on RAOs. Specifically, the paper evaluates a novel concept for wave estimation based on combined techniques using a wave frequency estimator, not dependent on RAOs, to detect wave frequency and, respectively, nonlinear least squares fitting to estimate wave amplitude and phase. The concept has been previously tested with only numerical simulations but in this study the techniques are applied to model-scale experiments. It is shown that the techniques successfully can be used to estimate the wave parameters of a regular wave train.

Fault diagnosis of active magnetic bearings based on Gaussian GLRT detector
Active magnetic bearings are progressively replacing conventional bearings in many industrial applications, particularly in the energy sector. Magnetic bearings have many advantages such as contactless support and clean operation; however their use also poses some challenges connected to their inherent open loop instability. Occurrence of faults in one or more
components of an active magnetic bearing may lead to loss of control of the rotor. Timely detection and isolation of faults in an active magnetic bearing could prevent hazardous system behaviour by enabling proper reconfiguration of the control system. A structural model of the bearing-rotor system is presented and used to perform a detectability and isolability analysis of faults in the magnetic actuator. Structural detectability and group-wise isolability is concluded for single and multiple faults in the actuators. A Gaussian generalized likelihood ratio test is proposed for detecting faults striking the electromagnet. The detector is capable of detecting and isolating the occurrence of faults in e.g. the windings of bearing by tracking changes in the mean value of a Gaussian distribution. The statistical distribution of the residuals in non faulty condition is characterized by experimental data of a full-scale bearing-rotor system. Verification of the detection performance is done through simulated data of a nonlinear model of the magnetic bearing calibrated against the real system.

**Adaptive Backstepping Control of Lightweight Tower Wind Turbine**

This paper investigates the feasibility of operating a wind turbine with lightweight tower in the full load region exploiting an adaptive nonlinear controller that allows the turbine to dynamically lean against the wind while maintaining nominal power output. The use of lightweight structures for towers and foundations would greatly reduce the construction cost of the wind turbine, however extra features ought be included in the control system architecture to avoid tower collapse. An adaptive backstepping collective pitch controller is proposed for tower point tracking control, i.e. to modify the angular deflection of the tower with respect to the vertical axis in response to variations in wind speed. The controller is shown to guarantee asymptotic tracking of the reference trajectory. The performance of the control system is evaluated through deterministic and stochastic simulations including an extreme wind gust event, and the feasibility of stabilizing the tower position while maintaining the rated power output is shown.
Collective Modular Underwater Robotic System for Long-Term Autonomous Operation

This paper provides a brief overview of an underwater robotic system for autonomous inspection in confined offshore underwater structures. The system, which is currently in development, consists of heterogeneous modular robots able to physically dock and communicate with other robots, transport tools and robots, and recharge their batteries while underwater. These properties will provide the system, when fully developed, with unique capabilities such as ability to adapt robotic morphology and function to the current task and tolerate failures leading to long-term autonomous operations.

General Information
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Experimental Investigations of Decentralised Control Design for the Stabilisation of Rotor-Gas Bearings

Rotor-gas bearings are attracting increasing interest because of their high speed capabilities, low friction and clean operation. However, hydrostatic rotor-gas bearings show reduced damping characteristics, which makes it challenging to operate the rotating machine at and about the resonance frequencies. Active lubrication of the journal during operations could enhance the damping and stabilisation characteristics of the systems, and this could be achieved by means of stabilising controllers. This paper investigates the feasibility of using reduced order models obtained through Grey-Box identification for the design of stabilising controllers, capable of enabling the active lubrication of the journal. The root locus analysis shows that two different control solutions are feasible for the dampening of the first two eigenfrequencies of the rotor-gas bearing in the horizontal and vertical directions. Hardening and softening P-lead controllers are designed based on the models experimentally identified, and salient features of both controllers are discussed. Both controllers are implemented and validated on the physical test rig. Experimental results confirm the validity of the proposed approach.

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Experimental Verification of a Global Exponentially Stable Nonlinear Wave Encounter Frequency Estimator

This paper presents a global exponential stability (GES) proof for a signal-based nonlinear wave encounter frequency estimator. The estimator under consideration is a second-order nonlinear observer designed to estimate the frequency of
a sinusoid with unknown frequency, amplitude and phase. The GES proof extends previous results that only guarantee
global K-exponential stability. Typical applications are control and decision-support systems for marine craft, where it is
important to know the sea state and wave frequency. The theoretical results are verified experimentally by analyzing data
from towing tank experiments using a container ship scale model. The estimates for both regular and irregular waves
confirm the results. Finally, the estimator is applied to full-scale data gathered from a container ship operating in the
Atlantic Ocean during a storm. Again the theoretical results are confirmed.

General information
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Gas Bearing Control for Safe Operation in Critical Speed Regions - Experimental Verification: Paper

Gas bearings are popular for their high speed capabilities, low friction and clean operation, but require low clearances and suffer from poor damping properties. The poor damping properties cause high disturbance amplification near the natural frequencies. These become critical when the rotation speed coincides with a natural frequency. In these regions, even low mass unbalances can cause rub and damage the machine. To prevent rubbing, the variation of the rotation speed of machines supported by gas bearings has to be carefully conducted during run-ups and run-downs, by acceleration and deceleration patterns and avoidance of operation near the critical speeds, which is a limiting factor during operation, specially during run-downs. An approach for reducing the vibrations is by feedback controlled lubrication. This paper addresses the challenge of reducing vibrations in rotating machines supported by gas bearings to extend their operating range. Using \(H\)-design methods, active lubrication techniques are proposed to enhance the damping, which in turn reduces the vibrations to a desired safe level. The control design is validated experimentally on a laboratory test rig, and shown to allow safe shaft rotation speeds up to, in and above the two first critical speeds, which significantly extends the operating range.

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We present a nonlinear adaptive path-following controller that compensates for drift forces through vehicle sideslip. Vehicle sideslip arises during path following when the vehicle is subject to drift forces caused by ocean currents, wind and waves. The proposed algorithm is motivated by a line-of-sight (LOS) guidance principle used by ancient navigators, which is here extended to path following of Dubins paths. The unknown sideslip angle is treated as a constant parameter, which is estimated using an adaptation law. The equilibrium points of the cross-track and parameter estimation errors are proven to be uniformly semiglobally exponentially stable (USGES). This guarantees that the estimated sideslip angle converges to its true value exponentially. The adaptive control law is in fact an integral LOS controller for path following since the parameter adaptation law provides integral action. The proposed guidance law is intended for maneuvering in the horizontal-plane at given speeds and typical applications are marine craft, autonomous underwater vehicles (AUVs), unmanned aerial vehicles (UAVs) as well as other vehicles and craft where the goal is to follow a predefined parametrized curve without time constraints. Two vehicle cases studies are included to verify the theoretical results.
Modelling and Identification for Control of Gas Bearings

Gas bearings are popular for their high speed capabilities, low friction and clean operation, but suffer from poor damping, which poses challenges for safe operation in presence of disturbances. Enhanced damping can be achieved through active lubrication techniques using feedback control laws. Such control design requires models with low complexity, able to describe the dominant dynamics from actuator input to sensor output over the relevant range of operation. The mathematical models based on first principles are not easy to obtain, and in many cases, they cannot be directly used for control design due to their complexity and parameter uncertainties. As an alternative, this paper presents an experimental technique for "in situ" identification of low complexity models of the entire rotor-bearing-actuator system. Using grey-box identification techniques, the approach is shown to be easily applied to industrial rotating machinery with gas bearings and to allow for subsequent control design. The paper shows how piezoelectric actuators in a gas bearing are efficiently used to perturb the gas film for identification over relevant ranges of rotational speed and gas injection pressure. Parameter-varying linear models are found to capture the dominant dynamics of the system over the range of operation. Based on the identified models, decentralised proportional control is designed and is shown to obtain the required damping in theory as well as in a laboratory test rig.
New Concepts for Shipboard Sea State Estimation

The wave buoy analogy is a tested means for shipboard sea state estimation. Basically, the estimation principle resembles that of a traditional wave rider buoy which relies, fundamentally, on transfer functions used to relate measured wave-induced responses and the unknown wave excitation. This paper addresses however a newly developed concept of the wave buoy analogy but the approach presented herein is, on the contrary, not relying exclusively on transfer functions. Instead, the method combines a signal-based part, estimating wave frequency, and a model-based part, estimating wave amplitude and phase, where only the model-based part depends on transfer functions whereas the signal-based part relies on the measured vessel response alone. Case studies in terms of hypothetical examples show that the method is capable to reconstruct fully the wave elevation process of a sinusoidal regular wave; which include estimation of the wave’s frequency, amplitude and phase. At this stage, the method is far from being a useful means in practical, real-situation applications but the method provides, indeed, a valuable step towards developing new approaches for shipboard sea state estimation.

General information
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Parametric roll resonance monitoring using signal-based detection

Extreme roll motion of ships can be caused by several phenomena, one of which is parametric roll resonance. Several incidents occurred unexpectedly around the millennium and caused vast fiscal losses on large container vessels. The phenomenon is now well understood and some consider parametric roll a curiosity, others have concerns. This study employs novel signal-based detection algorithms to analyse logged motion data from a container vessel (2800 TEU) and a large car and truck carrier (LCTC) during one year at sea. The scope of the study is to assess the performance and robustness of the detection algorithms in real conditions, and to evaluate the frequency of parametric roll events on the selected vessels. Detection performance is scrutinised through the validation of the detected events using owners' standard methods, and supported by available wave radar data. Further, a bivariate statistical analysis of the outcome of the signal-based detectors is performed to assess the real life false alarm probability. It is shown that detection robustness and very low false warning rates are obtained. The study concludes that small parametric roll events are occurring, and that the proposed signal-based monitoring system is a simple and effective mean to provide timely warning of resonance conditions.

General information
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Reconfigurable Control of Input Affine Nonlinear Systems under Actuator Fault

This paper proposes a fault tolerant control method for input-affine nonlinear systems using a nonlinear reconfiguration block (RB). The basic idea of the method is to insert the RB between the plant and the nominal controller such that fault tolerance is achieved without re-designing the nominal controller. The role of the RB is twofold: on one hand it transforms the output of the faulty system such that its behaviour is similar to that of the nominal one from the controller’s viewpoint; on the other hand it modifies the control input to the faulty system such that the stability of the reconfigured loop is preserved. The RB is realized by a virtual actuator and a reference model. Using notions of incremental and input-to-state stability (ISS), it is shown that ISS of the closed-loop reconfigured system can be achieved by the separate design of the virtual actuator. The proposed method does not need any knowledge of the nominal controller and only assumes that the nominal closed-loop system is ISS. The method is demonstrated on a dynamic positioning system for an offshore supply vessel, where the virtual actuator is designed using backstepping.
This paper describes an obstacle detection system for a high-speed and agile unmanned surface vehicle (USV), running at speeds up to 30 m/s. The aim is a real-time and high performance obstacle detection system using both radar and vision technologies to detect obstacles within a range of 175 m. A computer vision horizon detector enables a highly accurate attitude estimation despite large and sudden vehicle accelerations. This further facilitates the reduction of sea clutter by utilising an attitude based statistical measure. Full scale sea trials show a significant increase in obstacle tracking performance using sensor fusion of radar and computer vision.
Adaptive Passivity Based Individual Pitch Control for Wind Turbines in the Full Load Region

This paper tackles the problem of power regulation for wind turbines operating in the top region by an adaptive passivity based individual pitch control strategy. An adaptive nonlinear controller that ensures passivity of the mapping aerodynamic torque-regulation error is proposed, where the inclusion of gradient based adaptation laws allows for the on-line compensation of variations in the aerodynamic torque. The closed-loop equilibrium point of the regulation error dynamics is shown to be UGAS (uniformly globally asymptotically stable). Numerical simulations show that the proposed control strategy succeeds in regulating the power output of the wind turbine despite fluctuations of the wind field due to wake and turbulence, without overloading the pitch actuators.

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Parametric Roll - Risk Reduction through Real-time Detection
PAROLL is an innovative condition-monitoring system for the timely detection of parametric roll on merchant vessels. It has been invented and developed by the Technical University of Denmark. DNV GL and Wallenius Marine have supported the development and full-scale validation of this monitoring system.

General information
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Early Detection of Parametric Roll Resonance on Container Ships

Parametric roll resonance on ships is a nonlinear phenomenon where waves encountered at twice the natural roll frequency can bring the vessel dynamics into a bifurcation mode and lead to extreme values of roll. Recent years have seen several incidents with dramatic damage to container vessels. The roll oscillation, which is subharmonic with respect to the wave excitation, may be completely unexpected and a system for detection of the onset of such resonance could warn the navigators before roll angles reach serious levels. Timely warning could make remedial actions possible, such as change the ship's speed and course, to escape from the bifurcation condition. This paper proposes nonparametric methods to detect the onset of roll resonance and demonstrates their performance. Theoretical conditions for parametric resonance are revisited and are used to develop efficient methods to detect its onset. Spectral and temporal correlations of the square of roll with pitch (or heave) are demonstrated to be of particular interest as indicators. Properties of the indicators are scrutinized, and a change detector is designed for the Weibull-type of distributions that were observed from a time-domain indicator for phase correlation. Hypothesis testing for resonance is developed using a combination of detectors to obtain robustness. Conditions of forced roll and disturbances in real weather conditions are analyzed and robust detection techniques are suggested. The efficacy of the methodology is shown on experimental data from model tests and on data from a container ship crossing the Atlantic during a storm.
Observer Backstepping Control for Variable Speed Wind Turbine

This paper presents an observer backstepping controller as feasible solution to variable speed control of wind turbines to maximize wind power capture when operating between cut-in and rated wind speeds. The wind turbine is modeled as a two-mass drive-train system controlled by the generator torque. The nonlinear controller aims at regulating the generator torque such that an optimal tip-speed ratio can be obtained. Simply relying on the measured rotor angular velocity the proposed observer backstepping controller guarantees global asymptotic tracking of the desired trajectory while maintaining a globally uniformly ultimately bounded torsional angle. The proposed controller shows convincing performance when simulated in closed loop within a stochastic environment.

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Unmanned Water Craft Identification and Adaptive Control in Low-Speed and Reversing Regions

This paper treats L1 adaptive hovering control of an unmanned surface vehicle in a station-keeping mode where a region of zero control authority and under-actuation are main challenges. Low-speed and reversing dynamics are identified from full scale sea trials, and parameter uncertainty is estimated. With significant parameter variation, an L1 adaptive controller is employed for heading control. The L1 family of controllers allows for several topologies and an architecture is suggested that suits heading control of a vessel, the requirements of which differ from that of previous L1 literature. The control design is tackled directly in discrete time to allow a fast embedded implementation in the vehicle. Analysis of robustness, tracking performance and wave disturbance response are detailed in the paper.

Controlling Parametric Resonance: Induction and Stabilization of Unstable Motions

Parametric resonance is a resonant phenomenon which takes place in systems characterized by periodic variations of some parameters. While seen as a threatening condition, whose onset can drive a system into instability, this chapter advocates that parametric resonance may become an advantage if the system undergoing it could transform the large amplitude motion into, for example, energy. Therefore the development of control strategies to induce parametric resonance into a system can be as valuable as those which aim at stabilizing the resonant oscillations. By means of a mechanical equivalent the authors review the conditions for the onset of parametric resonance, and propose a nonlinear control strategy in order to both induce the resonant oscillations and to stabilize the unstable motion. Lagrange's theory is used to derive the dynamics of the system and input–output feedback linearization is applied to demonstrate the feasibility of the control method.
Detection of Parametric Roll on Ships

Recent years have shown several incidents with dramatic damage on container vessels caused by parametric resonance. When the resonance starts, the roll oscillation at a sub-harmonic frequency of the wave excitation may be completely unexpected. Timely warning about the onset of the resonance phenomenon could make the navigator change ship’s speed and heading, and these remedial actions could make the vessel escape the bifurcation. This chapter proposes non-parametric methods to detect the onset of parametric roll resonance. Theoretical conditions for parametric resonance are re-visited and signal-based methods are developed to detect its onset. Hypothesis testing is derived for the particular distribution of the indicators for resonance. Robustness is investigated by analyzing forced roll and disturbances in real weather conditions. The performance of the novel methods is demonstrated on experimental data from towing tank tests and data from a container ship passing an Atlantic storm.

L1 Adaptive Manoeuvring Control of Unmanned High-speed Water Craft

This work addresses the issue of designing an adaptive robust control system to govern the steering of a high speed unmanned personal watercraft (PWC) maintaining equal performance across the craft’s envelope of operation. The maneuvering dynamics of a high speed PWC is presented and a strong variation over the envelope of operational conditions, including speed, is highlighted. The complexity of the nonlinear dynamics is overcome through identification of linear models at different speed regimes. A gray-box identification is conducted from full scale experiments and results in a four degrees-of-freedom surge-sway-yaw-roll model. An L1 adaptive autopilot is then designed, which allows to achieve fast adaption to system parameters’ changes and robustness of the closed loop system.
Statistical Change Detection for Diagnosis of Buoyancy Element Defects on Moored Floating Vessels

Floating platforms with mooring systems are used extensively in off-shore operations. Part of the mooring systems are underwater buoyancy elements that are attached to the mooring lines. Loss or damage of a buoyancy element is invisible but changes the characteristics of the mooring system and alters its ability to provide the necessary responses to withstand loads from weather. Damage of a buoyancy element increases the operation risk and could even cause abortion during an oil-offloading. The objective of this paper is to diagnose the loss of a buoyancy element using diagnostic methods. After residual generation, statistical change detection scheme is derived from mathematical models supported by experimental data. To experimentally verify loss of an underwater buoyancy element, an underwater line breaker is designed to create realistic replication of abrupt faults. The paper analyses the properties of residuals and suggests a dedicated GLRT change detector based on a vector residual. Special attention is paid to threshold selection for non ideal (non-IID) test statistics.

General information
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A Nonlinear Observer for Estimating Transverse Stability Parameters of Marine Surface Vessels

This paper presents a nonlinear observer for estimating parameters associated with the restoring term of a roll motion model of a marine vessel in longitudinal waves. Changes in restoring, also referred to as transverse stability, can be the result of changes in the vessel's centre of gravity due to, for example, water on deck and also in changes in the buoyancy triggered by variations in the water-plane area produced by longitudinal waves – propagating along the fore-aft direction along the hull. These variations in the restoring can change dramatically the dynamics of the roll motion leading to dangerous resonance. Therefore, it is of interest to estimate and detect such changes.

General information
State: Published
Organisations: Automation and Control, Department of Electrical Engineering, University of Newcastle
Authors: Galeazzi, R. (Intern), Perez, T. (Ekstern)
Pages: 2967-2971
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Prediction of Parametric Roll Resonance by Multilayer Perceptron Neural Network

Parametric roll resonance is a ship stability related phenomenon that generates sudden large amplitude oscillations up to 30-40 degrees of roll. This can cause severe damage, and it can put the crew in serious danger. The need for a parametric rolling real time prediction system has been acknowledged in the last few years. This work proposes a prediction system based on a multilayer perceptron (MP) neural network. The training and testing of the MP network is accomplished by feeding it with simulated data of a three degrees-of-freedom nonlinear model of a fishing vessel. The neural network is shown to be capable of forecasting the ship’s roll motion in realistic scenarios.

Autonomous Supervision and Control of Parametric Roll Resonance

When ships sail in longitudinal waves, and the encounter frequency and wave length satisfy certain conditions, passage of wave crest and wave trough along the hull continuously amplifies the roll motion at half the frequency of encounter. This gives the onset of a resonance condition. The phenomenon can induce a rapid increase in roll motion that can reach 40 degrees or more. Recent incidents have shown that modern container ships and some fishing vessels are particularly prone to this due to their hull shape. Such incidents can result in damages counting to millions of USD. Theoretically, the resonance behaviour is well understood and it can be reproduced by quasi-periodic changes in parameters of nonlinear differential equations that describe ship motion. Practically, the challenge is whether detection and stabilization can be achieved in time to avoid damage. The research in this thesis has therefore two objectives. The first is to develop methods for detection of the inception of parametric roll resonance. The second is to develop control strategies to stabilize the motion after parametric roll has started. Stabilisation of parametric roll resonance points to two possible courses of action. One is a direct stabilisation through an increase of damping in roll, which increases the threshold that triggers the resonant motion. A second is to obtain a change in wave encounter frequency by means of changes in ship forward speed and/or heading. As direct stabilisation, this thesis considers the increase of roll damping by using fin stabilisers, which are controlled using integrator backstepping methods. As indirect stabilisation, a shift in the encounter frequency is considered by varying the ship forward speed. The speed controller is designed using nonlinear Lyapunov methods. The two control strategies are then combined to stabilise parametric roll resonance within few roll cycles. Limitations on the maximum stabilisable roll angle are analysed and linked to the integral rate saturation and hydrodynamic stall characteristics of the fin stabilisers. The study on maximum stabilisable roll angle leads to the requirements for early detection. Two novel detectors are proposed, which work within a short time prediction horizon, and issue early warnings of parametric roll inception within few roll cycles from its onset. The main idea behind these detection schemes is that of exploiting the link between the second harmonic of roll angle and the first harmonic of heave or pitch motions. A nonlinear energy flow
indicator, which measures the transfer of energy from the first harmonic of heave or pitch into the second harmonic of roll, is at the core of the first detector. The second detector relies on a driving signal that carries information about the phase correlation between either pitch or heave and roll. A generalised likelihood ratio test is designed to detect a change in distribution of the driving signal. The detectors are validated against experimental data of tests of a 1:45 scale model of a container ship. The validation shows excellent performance in terms of time to detect and false-alarm rate for both the proposed detectors. The detectors are the main contribution of this research. The thesis also offers a contribution regarding modeling. A 3 degree-offreedom nonlinear model in heave-pitch-roll of a container ship suitable for parametric roll resonance study is proposed. The model, which has been developed in collaboration with other researchers, provides a benchmark for the study and simulation of parametric roll over a large range of ship speeds and sea states. The results of this research have been published in articles enclosed in this dissertation and in an international patent application.

Detection of Parametric Roll Resonance on Ships from Indication of Nonlinear Energy Flow

The detection of the onset of parametric roll resonance on ships is of a central importance in order to activate specific control strategies able to counteract the large roll motion. One of the main priorities is to have detectors with a small detection time, such that warnings can be issued when the roll oscillations are about 5°. This paper proposes two different...
detection approaches: the first one based on sinusoidal detection in white gaussian noise; the second one utilizes an energy flow indicator in order to catch the onset of parametric roll based upon the transfer of energy from heave and pitch to roll. Both detectors have been validated against experimental data of a scale model of a container vessel excited with both regular and irregular waves. The detector based on the energy flow indicator proved to be very robust to different scenarios (regular/irregular waves) since it does not rely on any specific assumption on the signal to be detected.

General information
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Organisations: Automation and Control, Department of Electrical Engineering, Mathematical Statistics, Department of Informatics and Mathematical Modeling
Authors: Galeazzi, R. (Intern), Blanke, M. (Intern), Poulsen, N. K. (Intern)
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Parametric Roll Resonance Detection using Phase Correlation and Log-likelihood Testing Techniques
Real-time detection of parametric roll is still an open issue that is gathering an increasing attention. A first generation warning systems, based on guidelines and polar diagrams, showed their potential to face issues like long-term prediction and risk assessment. This paper presents a second generation warning system the purpose of which is to provide the master with an onboard system able to trigger an alarm when parametric roll is likely to happen within the immediate future. A detection scheme is introduced, which is able to issue a warning within five roll periods after a resonant motion started. After having determined statistical properties of the signals at hand, a detector based on the generalised log-likelihood ratio test (GLRT) is designed to look for variation in signal power. The ability of the detector to trigger alarms when parametric roll is going to onset is evaluated on two sets of experimental data, covering both regular and irregular seas in a model basin.

General information
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Organisations: Automation and Control, Department of Electrical Engineering, Mathematical Statistics, Department of Informatics and Mathematical Modeling
Authors: Galeazzi, R. (Intern), Blanke, M. (Intern), Poulsen, N. K. (Intern)
Pages: 316-321
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Stabilisation of Parametric Roll Resonance by Combined Speed and Fin Stabiliser Control
Parametric roll resonance on a ship is a condition where large roll motion develops rapidly in moderate head or following seas. The phenomenon is caused by bifurcation in the nonlinear equations of motion when a restoring moment is subject to periodic variation. This paper analyzes the stability of the nonlinear system and suggests active control of both ship
speed and fin stabilizers to stabilise the roll resonance condition. Lyapunov and backstepping designs are employed to achieve two nonlinear controllers, which are proved to stabilise the nonlinear system. The designed controllers are validated employing a high fidelity simulation model. The combined speed and fin stabiliser control is shown to efficiently drive the vessel out of the bifurcation condition and to quickly damp the residual roll motion.
Nonlinear Container Ship Model for the Study of Parametric Roll Resonance

Parametric roll is a critical phenomenon for ships, whose onset may cause roll oscillations up to 40°, leading to very dangerous situations and possibly capsizing. Container ships have been shown to be particularly prone to parametric roll resonance when they are sailing in moderate to heavy head seas. A Matlab/Simulink parametric roll benchmark model for a large container ship has been implemented and validated against a wide set of experimental data. The model is a part of a Matlab/Simulink Toolbox (MSS, 2007). The benchmark implements a 3rd-order nonlinear model where the dynamics of roll is strongly coupled with the heave and pitch dynamics. The implemented model has shown good accuracy in predicting the container ship motions, both in the vertical plane and in the transversal one. Parametric roll has been reproduced for all the data sets in which it happened, and the model provides realistic results which are in good agreement with the model tank experiments.

General information
State: Published
Organisations: Automation, Department of Electrical Engineering, Norwegian University of Science and Technology, Universidade Federal do Rio de Janeiro, University of Newcastle
Authors: Holden, C. (Ekstern), Galeazzi, R. (Intern), Rodríguez, C. (Ekstern), Perez, T. (Ekstern), Fossen, T. I. (Ekstern), Blanke, M. (Intern), Neves, M. D. A. S. (Ekstern)
Pages: 87-103
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Main Research Area: Technical/natural sciences

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BFI (2017): BFI-level 1
BFI (2016): BFI-level 1
Scopus rating (2016): SJR 0.319 SNIP 0.89
Scopus rating (2015): SJR 0.253 SNIP 0.757
Web of Science (2015): Indexed yes
Scopus rating (2014): SJR 0.317 SNIP 0.897
Web of Science (2014): Indexed yes
Scopus rating (2013): SJR 0.579 SNIP 1.211
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Scopus rating (2012): SJR 0.479 SNIP 1.36
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Scopus rating (2011): SJR 0.238 SNIP 0.841
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Scopus rating (2010): SJR 0.21 SNIP 0.545
Scopus rating (2009): SJR 0.267 SNIP 0.68
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Scopus rating (2008): SJR 0.165 SNIP 0.592
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Web of Science (2007): Indexed yes
Scopus rating (2006): SJR 0.118 SNIP 0.397
Scopus rating (2005): SJR 0.181 SNIP 0.424
Scopus rating (2004): SJR 0.1 SNIP 0
Scopus rating (2003): SJR 0.246 SNIP 0.371
On the Feasibility of Stabilizing Parametric Roll with Active Bifurcation Control

When parametric resonance occurs on a ship, large roll motion develops rapidly and severe damage on cargo is likely. Some vessels have even capsized in moderate seas for reasons believed to be parametric resonance. This paper revisits the analysis of parametric resonance and assess the possibility to dynamically modify the instability region where parametric roll can occur. It is shown how a control strategy for roll stabilization could be modified to change a bifurcation in roll motion and stabilize the motion, even after parametric resonance has started. The paper addresses issues of achievable performance and demonstrates the approach on a yaw-sway-roll-surge model of a containership.

Pitch Motion Stabilization by Propeller Speed Control Using Statistical Controller Design

This paper describes dynamics analysis of a small training boat and a possibility of ship pitch stabilization by control of propeller speed. After upgrading the navigational system of an actual small training boat, in order to identify the model of the ship, the real data collected by sea trials were used for statistical analysis and system identification. This analysis shows that the pitching motion is indeed influenced by engine speed and it is suggested that there exists a possibility of reducing the pitching motion by properly controlling the engine throttle. Based on this observation, a controller is designed using statistical optimal control. Controller robustness is investigated and recorded data of motion in a seaway are used to show it is feasible to reduce pitch motion in waves.
Projects:

Data-driven Condition Monitoring of Switches and Crossings
Department of Electrical Engineering
Period: 01/06/2016 → 31/05/2019
Number of participants: 3
PhD Student:
Barkhordari, Pegah (Intern)
Supervisor:
Blanke, Mogens (Intern)
Main Supervisor:
Galeazzi, Roberto (Intern)

Financing sources
Source: Internal funding (public)
Name of research programme: Forskningsrådsfinansiering
Project: PhD

Reconfigurable Modular Robotic System for Aquatic Environment
Department of Electrical Engineering
Automation and Control
Centre for Playware
National Institute of Aquatic Resources
Section for Oceans and Arctic
Department of Mechanical Engineering
Engineering Design and Product Development
Fluid Mechanics, Coastal and Maritime Engineering
Period: 01/02/2016 → 31/01/2018
Number of participants: 6
Acronym: REMORA
Project participant:
Christensen, David Johan (Intern)
Mariani, Patrizio (Intern)
Visser, Andre (Intern)
Özkil, Ali Gürcan (Intern)
Nielsen, Ulrik Dam (Intern)
Project Manager, academic:
Galeazzi, Roberto (Intern)

Dynamic Propeller Shaft Speed Control
Department of Electrical Engineering
Automation and Control
Department of Mechanical Engineering
Fluid Mechanics, Coastal and Maritime Engineering
Maersk Maritime Technology
Intelligent Quality Assessment of Railway Switches and Crossings

This project aims at significantly improving the safety, reliability and operational lifetime of the 3500 switches and crossings (S&Cs) in the Danish railway network. The project is a close cooperation between the Technical University of Denmark (DTU), the Danish rail infrastructure provider Rail Net Denmark and four affiliated European partners with significant expertise within this field. An inter-disciplinary scientific effort is employed to obtain enhanced rail transport reliability and regularity simultaneously with significant savings in S&Cs maintenance costs. The project results will make maintenance based on intelligent fault prediction tools, instead of the presently used regular planned inspections, and it will provide sophisticated tools to prevent hidden faults from developing to failure in the future. In a novel approach, the project will install state-of-the-art sensor technology in selected S&Cs and correlate dynamic parameters during train passage with static geometry data from conventional measurement vehicles. Monitoring of the dynamic responses will provide diagnosis of patterns that indicate when components or ballast begin to deviate from fully functional conditions. Modelling of dynamics will identify root causes to signs of degradation. Damage assessment of components identified by anomalous readings will be done by metallurgical examinations. Data and results will be processed by a holistic model that can produce Maintenance Performance Indicators (MPI) for the S&C condition. The correlation of sensor data to measuring vehicle data will allow existing data to be used reliably as input for the MPI model. It is expected that this project will enable optimisation of maintenance procedures, by which appropriate maintenance can be predicted in advance, thus avoiding unscheduled repairs and delays in the railway traffic.
Juul Jensen, Dorte (Intern)

**Financing sources**
Source: Public research council  
Name of research programme: Innovationsfonden  
Web address: http://innovationsfonden.dk/da  
Amount: 12,700,000.00 Danish Kroner  
Year of approval: 2014  
Project

**Fault Diagnosis and Optimal Control of Electro-Mechanical systems**
Department of Electrical Engineering  
Period: 15/12/2014 → 14/12/2017  
Number of participants: 7  
Phd Student:  
Sekunda, André Krabdrup (Intern)  
Supervisor:  
Poulsen, Niels Kjølstad (Intern)  
Santos, Ilmar (Intern)  
Main Supervisor:  
Niemann, Hans Henrik (Intern)  
Examiner:  
Galeazzi, Roberto (Intern)  
Kallesøe, Carsten Skovmose (Ekstern)  
Kinnaert, Michel (Ekstern)  

**Financing sources**
Source: Internal funding (public)  
Name of research programme: Institut stipendie (DTU)  
Project: PhD

**Exhaust Recirculation Control for Reduction of NOx from Large Two-stroke Diesel Engines**
Department of Electrical Engineering  
Period: 01/09/2013 → 12/04/2017  
Number of participants: 7  
Phd Student:  
Nielsen, Kræn Vodder (Intern)  
Supervisor:  
Hoffmann, Mark (Intern)  
Laursen, Morten (Intern)  
Main Supervisor:  
Blanke, Mogens (Intern)  
Examiner:  
Galeazzi, Roberto (Intern)  
Johansen, Tor Arne (Ekstern)  
Theotokatos, Gerasimos (Ekstern)  

**Financing sources**
Source: Internal funding (public)  
Name of research programme: Industrial PhD

**Relations**
Publications:  
Exhaust Recirculation Control for Reduction of NOx from Large Two-Stroke Diesel Engines  
Project: PhD

**Advanced Control of Smart Materials Applied to Sustainable Technology**
Department of Electrical Engineering
Period: 01/05/2013 → 07/09/2016
Number of participants: 7
Phd Student:
Theisen, Lukas Roy Svane (Intern)
Supervisor:
Galeazzi, Roberto (Intern)
Santos, Ilmar (Intern)
Main Supervisor:
Niemann, Hans Henrik (Intern)
Examiner:
Andreasen, Casper Schousboe (Intern)
Grigoriadis, Karolos M. (Ekstern)
Verhaegen, Michel (Ekstern)

Financing sources
Source: Internal funding (public)
Name of research programme: Institut stipendie (DTU) Samf.

Relations
Publications:
Advanced Control of Active Bearings - Modelling, Design and Experiments
Project: PhD

Model-Based Control Design for Flexible Rotors Supported by Active Tilting Pad Bearings
Department of Mechanical Engineering
Period: 01/04/2012 → 19/01/2017
Number of participants: 5
Phd Student:
Salazar, Jorge Andrés González (Intern)
Main Supervisor:
Santos, Ilmar (Intern)
Examiner:
Galeazzi, Roberto (Intern)
Glavatskih, Sergei (Ekstern)
Sahinkaya, Mehmet Necip (Ekstern)

Financing sources
Source: Internal funding (public)
Name of research programme: Stipendie fra udlandet

Relations
Publications:
Towards Model-Based Control Design for Flexible Rotors Supported by Active Tilting Pad Bearings - Theory & Experiment
Project: PhD

Autonomous Supervision and Control to Prevent Parametric Resonance
Department of Electrical Engineering
Period: 01/08/2006 → 03/03/2010
Number of participants: 6
Phd Student:
Galeazzi, Roberto (Intern)
Supervisor:
Jensen, Jørgen Juncher (Intern)
Main Supervisor:
Blanke, Mogens (Intern)
Examiner:
Santos, Ilmar (Intern)
Kinnaert, Michel (Ekstern)
Nijmeijer, Henk (Ekstern)

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Source: Internal funding (public)
Name of research programme: DTU-lønnet stipendie
Project: PhD