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# Buckling phenomenon for straight and curved pipe under pure bending

Yudo H.[a] , Yoshikawa T.[b]

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[b] Department of Marine System Engineering, Kyushu University, Fukuoka, Japan



## Abstract

Not only straight pipes, but also the curved ones are used in an actual pipeline. In designing such a pipeline, it is important to know the buckling strength of the pipe under various kinds of loads. Especially, it is well known that the buckling moment will be reduced by increasing the pipe's length. However, comprehensive studies for the buckling strength of straight and curved pipe under bending loads are still limited. In this research, the previous research for the buckling strength of pipe under bending moments was reviewed. It is well known that the cross-sectional oval deformation takes place


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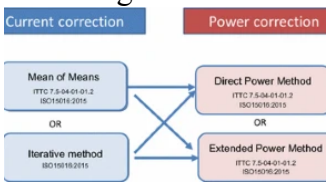


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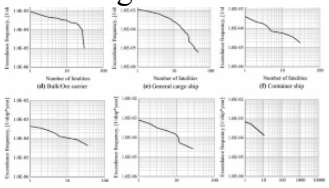

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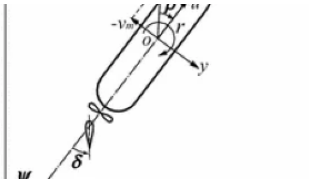

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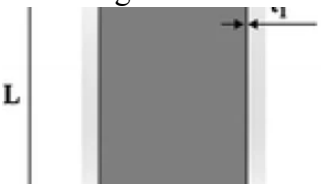


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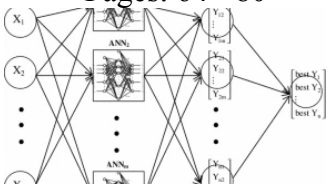

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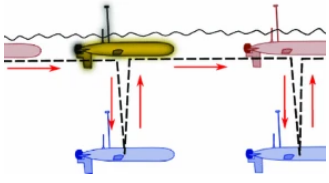

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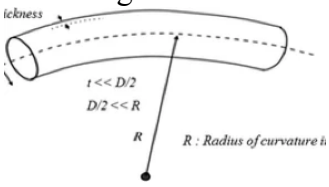


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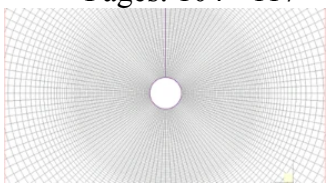

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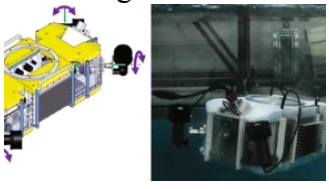

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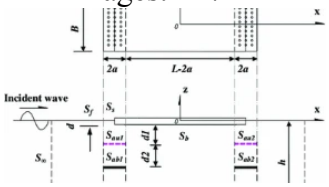


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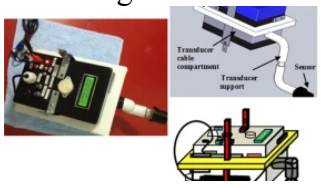


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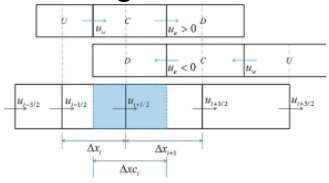

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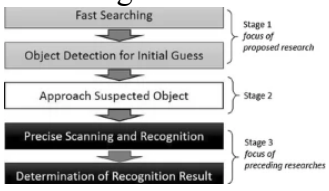


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ORIGINAL ARTICLE

# Buckling phenomenon for straight and curved pipe under pure bending

Hartono Yudo · Takao Yoshikawa

**Abstract** Not only straight pipes, but also the curved ones are used in an actual pipeline. In designing such a pipeline, it is important to know the buckling strength of the pipe under various kinds of loads. Especially, it is well known that the buckling moment will be reduced by increasing the pipe's length. However, comprehensive studies for the buckling strength of straight and curved pipe under bending loads are still limited. In this research, the previous research for the buckling strength of pipe under bending moments was reviewed. It is well known that the cross-sectional oval deformation takes place and the buckling strength of pipe is reduced due to this deformation. Therefore, secondly, the buckling phenomenon for a straight pipe under a pure bending moment was investigated by nonlinear FEA, considering the effect of a cross-sectional oval deformation by changing the varying of pipes, that is, the length-to-diameter ratio ($L/D$) varying from about 5 to 20 and the diameter-to-thickness ratio ($D/t$) varying from about 50 to 200. Thirdly, the buckling phenomenon for curved pipe was also investigated by changing the $R/D$ from 50 to 200 where $R$ is the curvature radius of curved pipe. From the results of the calculations for the straight pipe, the reduction rate of the buckling moment due to the oval deformation of pipe was clarified for various values of $L/D$ and $D/t$, not only in elastic buckling, but also in elasto-plastic buckling. For the curved pipe, it was explained that the buckling moment will be reduced by lowering the value of $R/D$.

**Keywords** Buckling strength · Straight pipe · Curved pipe · Oval deformation · Pure bending

**List of symbols**

| | |
|---|---|
| $D$ | Diameter of cylinder |
| $E$ | Young's modulus |
| $M$ | Applied moment |
| $M_a$ | Maximum moment in elasto-plastic analysis |
| $M_b$ | Buckling moment obtained by nonlinear calculation (in elastic) |
| $M_{cr}$ | Critical bending moment under axial compression |
| $M_p$ | Ultimate (plastic) moment |
| $M_y$ | Yield moment |
| $r$ | Radius of cylinder |
| $R$ | Radius of curvature in curved pipe |
| $t$ | Nominal wall thickness |
| $v$ | Poisson's ratio |
| $\sigma_{cr}$ | Critical buckling stress under axial compression |
| $\sigma_y$ | Yield stress |

## 1 Introduction

The problem of buckling for a circular cylindrical shell has been widely investigated due to its great importance in the design of marine structures. Both the straight and curved pipes are used in an actual pipeline. At the time of operation, the pipeline will be subject to a wide range of loads. Buckling of structural components under various types of loading is a common cause of fatal failure in a structure.

H. Yudo (✉)
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J Mar Sci Technol (2015) 20:53–63
DOI 10.1007/s00773-014-0268-z

REVIEW ARTICLE

# Multi-objective optimum design of a buoy for the resonant-type wave energy converter

**Hyeok-Jun Koh · Won-Sun Ruy · Il-Hyoung Cho · Hyuck-Min Kweon**

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**Abstract** This paper deals with the resonant type of wave energy converter (WEC) and the determination method of its geometric parameters, which were obtained to construct a robust and optimal structure. The optimization problem is formulated with the objectives of simultaneously maximizing the absorbed power output, which is mainly related to optimal power take-off damping, and minimizing the production cost by the volume of the required sheet plate using a weighting method. The constraints are composed of the response surfaces that indicate the resonance period (heave, pitch) and the meta-center height of the buoy. The signal-to-noise ratio calculated from the normalized multi-objective results with the weight factor can be used to help select the robust design level. In order to obtain a sample data set, the motion responses of the power buoy were analyzed using a commercial code based on the boundary element method. We present the Pareto-optimal set to reveal the relationship between the power and the volume of a sheet plate. Lastly, the power efficiency of the WEC with the optimum design variables is estimated as the captured wave ratio resulting from the absorbed power. The result of the WEC design is economically optimal and satisfies given constraints.

**Keywords** Resonance · Wave energy converter · Boundary element method · Multi-objective optimization · Response surface method · Captured wave ratio

## 1 Introduction

A wide variety of wave energy technology research is being carried out to be a commercial model using theory, numerical analysis, and experiment for the various types at several stages of development since 1970s [1–3]. Concepts of wave energy devices are mainly classified into two categories according to the principle of kinetic energy conversion(e.g., oscillating bodies, oscillating water columns, run-up) and the type of foundation(e.g., fixed/submerged, floating). In order to determine the optimal type and location of a WEC, surveying the wave energy resource distribution as preliminary data for wave power generation is a crucial factor. Thus, the atlas of global wave energy was developed by Cornett [4] using archived NOAA Wavewatch-III (NWW3) from 1996 to 2007, and the seasonal variability index (SV) and the monthly variability index (MV) were proposed as new parameters that were easy to compute and serve to quantify the seasonal and monthly variability of wave energy resources. The findings indicate that the wave energy density would concentrate at latitudes of 40°–60°N and 40°–60°S, and that the maximum annual average wave power is distributed southwest of Australia in the southern hemisphere and south of Iceland in the northern hemisphere. Based on this statistical wave energy data, there has been heavy support

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REVIEW ARTICLE

# Application of ensemble neural networks to prediction of towboat shaft power

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**Abstract** In this paper towboat shaft power was predicted using various artificial neural networks. This work is a step toward reducing errors in the prediction of towboat power as well as providing better understanding of powering characteristics by the crew of the towboat. An ensemble neural network (ENN) and the single neural network (ANN) with two hidden layers are proposed to predict towboat shaft power. These two models were compared on the basis of their calculated root mean squared errors, mean absolute errors and relative errors. The database used for training and testing of the proposed ANN and ENN has been collected from the full-scale speed-power trials. Trials are conducted on selected towboats and convoys of barges. The goal of the paper is to show that ENN can be applied on towboat shaft power prediction and can improve the accuracy of the results over the single ANN. Computational results from this numerical example show that ENN definitely outperforms single ANN with two hidden layers. The contribution of this paper is a proposal to use an AIC-based ENN method for predicting towboat shaft powers. The paper is the first one that addresses AIC-based ENN method to predict towboat shaft powers.

**Keywords** Full-scale trials · Towboat shaft power · Artificial neural networks · Ensemble neural networks

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**List of symbols**

| | |
|---|---|
| AIC | Akaike information criterion |
| $AIC_c$ | Corrected AIC value |
| $B$ | Pushed convoy beam in meters (m) |
| $\beta$ | Constant |
| $\Delta AIC_c$ | Modified delta_AIC value |
| DIV | Diversity of the component network |
| $\eta^1$ | Relative error calculated for training data set |
| $\eta^2$ | Relative error calculated for testing data set |
| $f^1$ | Relative frequencies of the relative errors calculated for training data set |
| $f^2$ | Relative frequencies of the relative errors calculated for testing data set |
| $F_n$ | Froude number |
| $K$ | Total number of estimated parameters of the ANN model |
| $L$ | Pushed convoy length in meters (m) |
| $\Lambda$ | Weight of the component network |
| $N$ | Sample size or number of all measured data |
| N | The set of all natural numbers |
| $n_s^1$ | Number of times the relative errors appear in subinterval $s$ calculated for training data set |
| $n_s^2$ | Number of times the relative errors appear in subinterval $s$ calculated for testing data set |
| $N_h$ | Number of hidden neurons |
| $N_i$ | Number of input neurons |
| $N_{tr}$ | Number of training data |
| $O$ | Set of all shaft powers obtained through measurements (real outputs) |
| $\hat{O}$ | Set of all predicted shaft powers |
| $\hat{O}^1$ | Set of all towboat shaft powers predicted with training data set by ENN |
| $\hat{O}^2$ | Set of all towboat shaft powers predicted with testing data set by ENN |