

Comparative Analysis of Vortex-Induced Vibration Models on Risers Caused by Vessel Motion

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Abstract
Over the past recent years, several models for prediction of vortex-induced vibrations on risers and cables in slender marine structures have been proposed. This study provided a consistent discussion and critical evaluation of the most commonly applied models, highlighting their strengths, mathematical equations, principles, assumptions and their implications, and the apparent limitations associated with each model. The study critically evaluated and compared vortex-induced vibration models for dynamic response of water risers induced by vessel motion using a multi-criteria analysis tool (AHP). Seven alternatives which include: the DNV model, the LIC engineering model, the MARINTEK model, the MIT-Trianfyllou model, the MIT-Vandiver model, the NTH model and the UCL model were compared against a set of five broad criteria which include: Robustness, Reliability, and Accuracy, Time, Ease of application and cost. The robustness as a broad criterion contains sub-criteria like Reynold's number range for which the simulation is valid, ability to be deployed for multimode problems, ability to describe spatial attenuation, ability to define excitation zones and how the load process is correlated in the zone. From the AHP analysis, the UCL model came out on top as the best and optimum VIV model compared to the other alternatives with an overall priority score of 1.3694. MIT-Vandiver came second with an overall priority score of 0.9656. The worst model from the outcome of the AHP analysis is the DNV model with an overall priority score of 0.6972.
Keywords: vortex-induced vibration, optimum VIV model, multi-criteria analysis tool, vortex-induced model comparison
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1. Introduction

The occurrence of vortex-induced vibrations, together with vortex flow, has been studied in some research works from both physical and mathematical views. Yet, the prediction of the deep-water system's vibration as a result of vortex flow has remained unclear and challenging as a research area. In the recent pasts, the impact of the vortex-induced vibrations on subsea systems has been considered for an in-depth understanding by the petroleum industry (Li *et al*., 2013). Still, the industry has been focusing majorly on experimental results for riser VIV design. However, the experiment has obvious drawbacks, including "facility availability and capacity limits, model scale limit, the challenge of current profile generation, cost concerns, etc.…" As a result of the limitations of experimental methods and as an alternative method to the expensive and time-wasting experimental solutions, numerical simulation tools have been developed. Nevertheless, most of the commercial software is incorporated with the different models which the mathematical principles and underlying assumptions associated with them are not known. Hence, they make the study of such a phenomenon not to be precise and reliable (Kim and Lee, 2012).

several methods have been developed during the last two decades, for the prediction of vortex-induced vibrations (VIV) of slender marine structures have been published. The various methods vary considerably in terms of their underlying assumptions, mathematical formulations, and how experimental results are considered. It is, therefore, reasonable to believe that such models will give different results if they are applied to identical problems. For a given application, some models must be better than others. Despite this, few if any have tried to evaluate and compare these models critically. This present study will carry out such comparisons and evaluations.

The focus of this study is to critically evaluate and compare vortex-induced vibration models for dynamic response of water risers induced by vessel motion using a multi-criteria analysis tool. Other objectives of the study include:

- To gain knowledge on the general aspects of VIV.
- Comparatively, analysed the strengths and limitations of the existing VIV models using a multi-criteria decision tool (Analytic Hierarchy Process).
- Propose the best VIV model for incorporation into the software

2. Structure of the Model (The AHP Procedure)

i. The first step, a complex decision problem, is structured as a hierarchy: A complex multi-criteria decision model (MCDM) has been initially broken down by Analytic Hierarchy Process (AHP) into a hierarchy of interrelated decision elements (criteria, decision alternatives). The objectives, criteria and alternatives are arranged in a hierarchical structure like a family tree (in the AHP process). A hierarchy has at least three levels: the overall goal of the problem at the top, the define alternatives in the middle by the multiple criteria, and decision alternatives at the bottom, as shown in figure 1. In figure1, the C1-C5 depicts the set of broad criteria on which the comparison is based, and A1-A7 are the sets of alternatives to be compared.

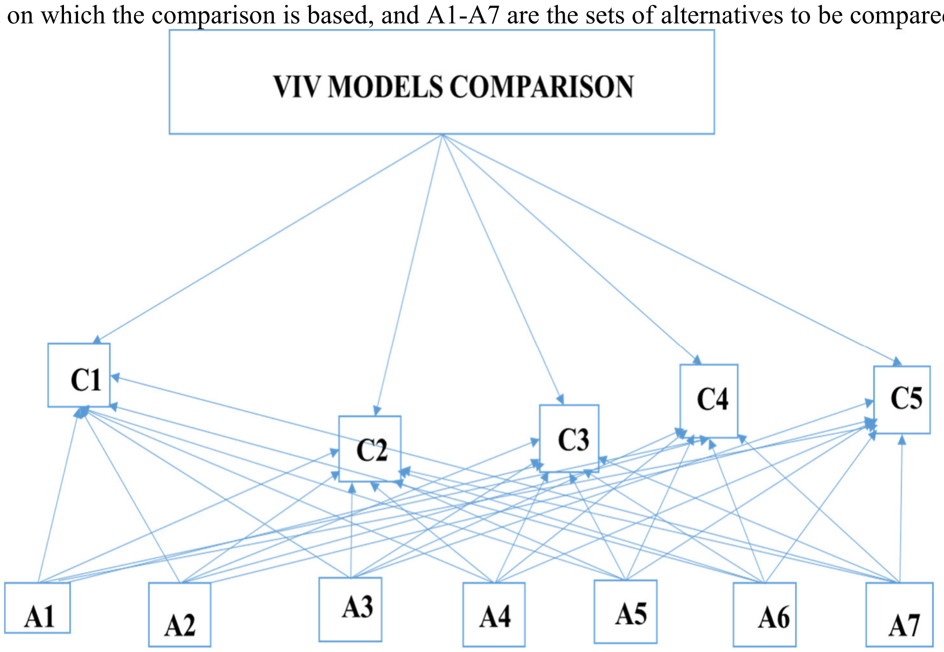

Figure 1: Hierarchy for VIV Models Comparison

ii. The second step, once the hierarchy is built, the decision-makers systematically evaluate by comparing the elements at its various alternatives to one another two at a time, concerning their impact on criteria element above them in the hierarchy. The numerical values that can be processed and compared over the entire range of the problem, when AHP converts the evaluations to numerical values. A numerical weight or priority is derived for each alternative element of the hierarchy, allowing diverse and often incommensurable alternative elements to be compared to one another rationally and consistently.

iii. The numerical priorities are calculated for each of the decision alternatives in the final step of the process. As the process allow a straightforward consideration of the various courses of action due to the numbers that represent the alternatives' relative ability to achieve the decision goal. Each of these judgments is then assigned an integer on a scale.

In this study, the original definition of scale given by Saaty (1980) was adopted. Table 1 shows the scale and their relative importance, as explained in it.

Table 1: The Saaty (1980) Rating Scale

Scale	The relative importance of the element	Explanation
1	Equally important	i and j are equally important
2		
3	Moderately important	i is moderately more important than j
4		
5	Strongly important	i is strongly more important than j
6		
7	Very strongly important	i is very strongly more important than j
8		
9	Extremely important	i is extremely more important than j
2,4,6,8	Intermediate values	used when a compromise is needed

2.1 Pairwise Comparison Matrix

Given a set of '*A*' alternatives: $A_1, A_2, A_3 \ldots A_n$ and a set of C criteria $C_1, C_2, C_3 \ldots C_n$, the data of a decision matrix will be given as: $a_{11}=(A_1,A_1)$; $a_{12} = (A_1,A_2) \ldots a_{1n} = (A_1,A_n)$; $a_{21} = (A_2,A_1)$; $a_{22} = (A_2,A_2) \ldots a_{2n} = (A_2,A_n)$.

The form of square matrix n x n, where n is the number of alternatives or criteria is used to carry out the pairwise comparison table mathematically. Although, the estimated judgment weights are the elements of the matrix, the relative importance among alternatives or criteria, as explained earlier (table 1). For example, the pairwise comparison matrix A, in which the element aij of the matrix is the relative importance of the ith factor concerning the jth factor and reciprocals are assigned automatically as:

$$A = \begin{bmatrix} 1 & a_{12} \cdots & a_{1n} \\ 1/a_{12} & 1 & a_{2n} \\ \vdots & \ddots & \vdots \\ 1/a_{1n} & \cdots & 1 \end{bmatrix}$$

2.2 Calculating the weights and determine the consistency for each level

Weights are calculated from the pairwise comparison matrices. The first step would be, to sum up, the values of each row in the comparison matrix. The row sums are then added to give the total sum. The row sum is then divided by the total sum. The weight for each row is given by the formula below:

$$Weight = \frac{row\ sum}{total\ sum} \quad (3.1) \quad (1)$$

This step is to find the relative priorities of criteria or alternatives implied by these comparisons. The relative priorities are worked out using the theory of eigenvector. Moreover, the consistency check should be done at each stage of the selection process. Three components are needed from the analysis, namely the Consistency Index (CI), Random Consistency Index (RI) and Consistency Ratio (CR). The following techniques are used to determine the above-said elements of calculation.

$$CI = \frac{\lambda_{max} - n}{n-1} \quad (3.2) \quad (2)$$

Where λ_{max} is the maximum eigenvalue and n is the size of the pairwise comparison matrix (i.e., the number of criteria).

Table 2: Saaty (1980) Random consistency Index (RI)

N	1	2	3	4	5	6	7	8	9	10
RI	0	0	0.58	0.9	1.12	1.24	1.32	1.41	1.45	1.49

The obtained CI value is compared with the random index RI given in Table 2. Table 2 had been calculated as an average of CI's of many thousand matrices of the same order whose entries were generated randomly from the scale 1 to 9 with reciprocal effect. The simulation results of RI for matrices of size 1 to 10 had been developed by Saaty (1980) and are given in Table 2. The ratio of CI and RI for the same order matrix is called the consistency ratio CR.

Thus, the consistency ratio (CR) is obtained by using,

$$CR = \frac{CI}{RI} \quad (3.3) \quad (3)$$

In general, a consistency ratio of 10% (0.1) or less is usually acceptable. If inconsistency of judgments within the matrix has occurred, then the evaluation process should be reviewed and improved upon it. At the final step of the calculation, the overall preference matrix would be constructed by multiplying all the weights with the factors; therefore, the results are added to get the composite score of each factor.

From figure1, the present study has seven alternatives which include: the DNV model, the LIC engineering model, the MARINTEK model, the MIT-Trianfyllou model, the MIT-Vandiver model, the NTH model and the UCL model. In this study, these models would be compared against a set of five broad criteria which include: Robustness, Reliability & Accuracy, Time, Ease of application and cost. The robustness as broad criteria contains sub-criteria like Reynold's number range for which the simulation is valid, ability to be deployed for multimode problems, ability to describe spatial attenuation, ability to define excitation zones and how the load process is correlated in the zone.

3 Results and Discussions

3.1 Results

To commence the AHP analysis, pairwise comparison of the criteria must be made. To accomplish this, questions are asked on how significant one criterion is in comparison to the other. To reliably provide answers to these questions, experts opinions were sought for in addition to the detailed literature review. With this, the decisions below were taken with respect to the importance of one criterion relative to the other:

3.1.1 Assignment of Scale of Relative Importance

1. If ease of application = x; time=x, cost=3x, reliability & accuracy=5x, robustness=5x

2. If time=x; cost=3x, reliability & accuracy=5x, robustness=5x
3. If cost=x; reliability & accuracy=5x, robustness=5x
4. If reliability & accuracy=x; robustness=x.

The meaning of the assigned importance is explained in table1, 3x means the criterion is moderately more important than the criterion it is being compared with, while 5x means that the criterion is strongly more important than the criterion it is being compared with. These assigned scales of relative importance imply that reliability & accuracy, and robustness are the most important factors to be considered in the choice of a model. Also, from expert opinions and the review of literature, the weight of each alternative with respect to the different criteria are provided in table 3. The score of the alternative models (table 3) was guided by the works of Carl and Karl (1997).

Table 3: Score of Alternative 'A' with respect to criterion 'C' (adopted from Carl and Karl, 1997)

Criteria						Remarks
Alternatives	**Robustness**	**Time**	**Cost**	**Ease of Application**	**Reliability & Accuracy**	(Score of option with respect to a criterion range from 1-10). 1 means poor and 10 implies excellent
DNV	**4**	**4**	**4**	**5**	**5**	
LICengineering	**5**	**5**	**6**	**4**	**6**	
MARINTEK	**4**	**5**	**6**	**6**	**5**	
MIT-Triantafyllou	**5**	**6**	**6**	**5**	**6**	
MIT-Vandiver	**6**	**5**	**5**	**7**	**7**	
NTH	**4**	**7**	**6**	**7**	**4**	
UCL	**5**	**6**	**6**	**6**	**6**	

Table 3 shows that for robustness, the MIT-Vandiver is the best model, for time to achieve simulation results, the NTH is the best, for computational cost, DNV is the worst, for ease of application, the LIC engineering and reliability of results, the MIT-Vandiver is the best.

3.1.2 Pairwise Matrix

Applying AHP in the analysis, the pair-wise comparison matrix is constructed, as shown in table 4. In table 4, the row elements have been divided by the column elements. Also, the sum of each column element has been noted.

Table 4: Pair-wise Comparison Matrix

Criteria	Ease	Time	Cost	Reliability & accuracy	Robustness
Ease	1.00	1.00	0.33	0.20	0.20
Time	1.00	1.00	0.33	0.20	0.20
Cost	3.00	3.00	1.00	0.20	0.20
Reliability & accuracy	5.00	5.00	5.00	1.00	1.00
Robustness	5.00	5.00	5.00	1.00	1.00
Sum	**15**	**15**	**11.66**	**2.6**	**2.6**

The next step is to normalize the pairwise matrix by dividing the elements of each column by the sum of the column. The outcome of this step is provided in Table 5:

Table 5: Normalized Pairwise Comparison Matrix

Criteria	Ease	Time	Cost	Reliability & accuracy	Robustness
Ease	0.0667	0.067	0.0283	0.0769	0.0769
Time	0.0667	0.067	0.0283	0.0769	0.0769
Cost	0.2000	0.2	0.0858	0.0769	0.0769
Reliability & accuracy	0.3333	0.333	0.4288	0.3846	0.3846
Robustness	0.3333	0.333	0.4288	0.3846	0.3846

After normalizing the pairwise matrix, the criteria weight is calculated by averaging all the elements in the row. That is the sum of the row elements divided by the number of criteria, which is 5 in this study. The outcome of this step is provided in Table 6:

Table 6: Criteria Weight Computation

Criteria	Ease	Time	Cost	Reliability & accuracy	Robustness	Criteria Weight
Ease	0.0667	0.067	0.0283	0.0769	0.0769	0.06316
Time	0.0667	0.067	0.0283	0.0769	0.0769	0.060976
Cost	0.2	0.2	0.0858	0.0769	0.0769	0.12792
Reliability & accuracy	0.333	0.333	0.4288	0.3846	0.3846	0.3728
Robustness	0.333	0.333	0.4288	0.3846	0.3846	0.3728

To check whether the calculated values are correct or not, the consistency is calculated. To do this, the non-normalized (initial) pair-wise comparison matrix is used. Each value in the column is multiplied with the criteria value, and the result is provided in Table 7 below:

Table 7: Consistency Computation

Criteria	Ease	Time	Cost	Reliability & accuracy	Robustness
Ease	0.063	0.061	0.042	0.075	0.075
Time	0.063	0.061	0.042	0.075	0.075
Cost	0.189	0.183	0.128	0.075	0.075
Reliability & accuracy	0.316	0.305	0.640	0.373	0.373
Robustness	0.316	0.305	0.640	0.373	0.373

At this point, the weighted sum value is calculated by taking the sum of each element in the row. The result is shown in Table 8:

Table 8: Weighted Sum Computation

Criteria	Ease	Time	Cost	Reliability & accuracy	Robustness	Weighted Sum value
Ease	0.063	0.061	0.042	0.075	0.075	0.315
Time	0.063	0.061	0.042	0.075	0.075	0.315
Cost	0.189	0.183	0.128	0.075	0.075	0.649
Reliability & accuracy	0.316	0.305	0.640	0.373	0.373	2.006
Robustness	0.316	0.305	0.640	0.373	0.373	2.006

The ratio of the weighted sum value and the criteria weight is then computed. The outcome is shown in Table 9:

Table 9: Ratio of Weighted sum value to Criteria weights

Weighted Sum value	Criteria weight	Ratio
0.3177	0.0660	4.995
0.3177	0.0660	5.174
0.4679	0.0933	5.077
1.9009	0.3874	5.381
1.9009	0.3874	5.381

λ_{max} is calculated by taking the average of the ratio values. From table 9, the average of the ratios is computed by adding the ratio and dividing the sum by the number of criteria (5). The result gave $\lambda max = 5.201$. The consistency index C.I is computed using equation 2, and the result after the computation gave $C.I = 0.05025$

Then the Consistency Ratio (C.R) is calculated as a ratio of Consistency Index (C.I) to Random Index (R.I) (see Eqn. 3). The Random Index table is shown in table 2. From table 2, the Random Index value for 5 criteria is given as 1.12. Therefore, computing the Consistency Ratio gave C.R = 0.045. Since the C.R value is less than 10% (0.10) which is the standard inconsistency value, therefore our matrix is reasonably consistent, and our generated criteria weight is shown in Table 10:

Table 10: Validated Criteria Weight

Criteria	Criteria Weight
Ease	0.0660
Time	0.0660
Cost	0.0933
Reliability & accuracy	0.3874
Robustness	0.3874

From table 10, it can be seen that the reliability and accuracy and robustness have the highest weight and therefore are the most important criteria.

3.1.3 Prioritization

These validated weights would now be used for the final step of the AHP analyses.

In this step, table 3 will be normalized by converting the matrix elements to 0-1. This is done by dividing each column element by the best criteria value on the column. The outcome of this normalization is shown in Table 11:

Table 11: Normalized Values for the Score of Alternative 'A' with respect to Criteria 'C.'

	Criteria				
Alternatives	**Robustness**	**Time**	**Cost**	**Ease of application**	**Reliability & accuracy**
DNV	0.6667	0.5714	0.6667	0.7143	0.7143
LICengineering	0.8333	0.7143	1.0000	0.5714	0.8571
MARINTEK	0.6667	0.7143	1.0000	0.8571	0.7143
MIT-Triantafyllou	0.8333	0.8571	1.0000	0.7143	0.8571
MIT-Vandiver	1.0000	0.7143	0.8333	1.0000	1.0000
NTH	0.6667	1.0000	1.0000	1.0000	0.5714
UCL	0.8333	0.8571	1.0000	0.8571	0.8571

3.1.4 Model synthesis

The next step is to multiply the normalized values in each column of table 11 with the corresponding criteria weight of the column. The outcome of this step is shown in Table 12:

Table 12: Model Synthesis

	Criteria				
Alternatives	**Robustness**	**Time**	**Cost**	**Ease of application**	**Reliability & accuracy**
DNV	0.0440	0.0377	0.0622	0.2767	0.2767
LICengineering	0.0440	0.0471	0.0933	0.2213	0.3320
MARINTEK	0.0440	0.0471	0.0933	0.3320	0.2767
MIT-Triantafyllou	0.0550	0.0566	0.0933	0.2767	0.3320
MIT-Vandiver	0.0660	0.0471	0.0777	0.3874	0.3874
NTH	0.0440	0.0660	0.0933	0.3874	0.2213
UCL	0.5556	0.0566	0.0933	0.3320	0.3320

To calculate the overall priorities of the alternatives, the sum of the row elements in table 12 is taken. The result is shown in Table 13.

Table 13: Overall Priorities for the Transport Technologies

Alternatives	**Overall Priority (AHP Score)**
DNV	0.6972
LIC engineering	0.7378
MARINTEK	0.7931
MIT-Triantafyllou	0.8135
MIT-Vandiver	0.9656
NTH	0.8120
UCL	1.3694

3.2 Discussion

Therefore, having completed the AHP analyses. Then giving the importance of each criterion (robustness of the model, ease of application, time, computational cost and reliability & accuracy of results), the UCL model came out on top as the best and optimum VIV model compared to the other alternatives with an overall priority score of 1.3694. MIT-Vandiver came second with an overall priority score of 0.9656. The worst model from the outcome of the AHP analysis is the DNV model with an overall priority score of 0.6972.

While the UCL model has emerged as the best VIV model following the AHP steps in this study, it is good to note that it still has some limitations. Therefore, more efforts should be made in developing more sophisticated models and methodologies for evaluating VIV that would overcome all the limitations associated with the current models.

VIV is a key source of fatigue damage for the marine riser. Though the VIV could be reduced via strakes or fairings, the economic implication of the hardware and installation is on the high side. Hence, the study focus on the riser VIV has been on the rise in the petroleum industry to attain a safe and cost-effective design. The deep-water platforms must function optimally with minimum downtime as unplanned interventions are very costly. Therefore, it is ideal to ensure that the facilities can withstand the prevailing environmental conditions and prevent disasters.

During the last two decades, several methods for the prediction of vortex-induced vibrations (VIV) of slender marine structures have been published. These methods vary considerably in terms of their basic assumptions, mathematical formulations, and how experimental results are considered. It is, therefore, reasonable to believe that such models will give different results if they are applied to identical problems. For a given application, some models must be better than others. Despite this, few if any have tried to evaluate and compare these models critically. Therefore, this study critically evaluated the existing VIV models and comparatively analysed the models using AHP.

4. Conclusion and Recommendations

4.1 Conclusion

In the recent pasts, the impact of the vortex-induced vibrations on subsea systems has been considered for an in-depth understanding by the petroleum industry. The industry has been focusing majorly on experimental results for riser VIV design. However, an experiment has obvious drawbacks, including “facility availability and capacity limits, model scale limit, the challenge of current profile generation, cost concerns, etc.” As a result of the limitations of experimental methods and as an alternative method to the expensive and time-wasting experimental solutions, numerical simulation tools have been developed. But most of the commercial software is incorporated with the different models which the mathematical principles and basic assumptions associated with them are not known. Hence, they make the study of such a phenomenon not to be precise and reliable.

Therefore, this study critically evaluated and compared vortex-induced vibration models for dynamic response of water risers induced by vessel motion using a multi-criteria analysis tool (AHP). The Seven alternatives include the DNV model, the LIC engineering model, the MARINTEK model, the MIT-Trianfyllou model, the MIT-Vandiver model, the NTH model, and the UCL model. All the mentioned methods were compared against a set of five broad criteria which include: Robustness, Reliability & Accuracy, Time, Ease of application and cost. The robustness as broad criteria contains sub-criteria like Reynold's number range for which the simulation is valid, ability to be deployed for multimode problems, ability to describe spatial attenuation, ability to define excitation zones and how the load process is correlated in the zone. From the AHP analysis, the UCL model came out on top as the best and optimum VIV model compared to the other alternatives with an overall priority score of 1.3694. MIT-Vandiver came second with an overall priority score of 0.9656. The worst model from the outcome of the AHP analysis is the DNV model with an overall priority score of 0.6972.

4.2 Recommendations

The result of the critical evaluations conducted in this study has shown that the existing models have some limitations. Therefore, more efforts should be made in developing more sophisticated models and methodologies for evaluating VIV that would overcome all the limitations associated with the current models.

Over the past recent years, several different models for prediction of vortex-induced vibrations of slender marine structures such as risers and cables have been proposed. This study has provided a consistent discussion and critical evaluation of the most applied models, highlighting their strengths, mathematical equations, principles, assumptions and their implications, and the obvious limitations associated with each model. This study also went further to comparatively analysed the models. This work will guide marine and subsea engineers on their choice of model for predicting VIV having shown when and where each of the models is applicable or not. This report will serve as reference material for the subsea industry and other researchers who are interested in this field of study.

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