Modelling Techniques for the Dynamic Response of Cable-Stayed Masts

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SUMMARY This paper looks into two methods that can be used to perform a dynamic analysis of a cable stayed mast to alongwind loading. It also looks into optimising the implementation procedure for one of them. A comparison of the dynamic response results with the Basic Design Approach (Static Analysis) from the recently released Australian code AS3995 is used as a basis for illustrating accuracy of these models/methods.

1 INTRODUCTION

The release of the Australian Standard AS3995 Design of Steel Lattice Towers and Masts (1), has given designers specific advice when considering special structures. The advice offered distinguishes structures which are potentially wind sensitive. Reference is made to simplified techniques for the assessment of this dynamic excitation as found in Davenport and Sparling (2), (a simplified statistical approach based on an extended gust factor method, and a patch loading method that has been calibrated).

This paper looks at the implementation, and optimisation of the so-called "Statistical method" of Gerstoft and Davenport. It then compares the results found for the dynamic response with the basic design approach (3 second gust) Static Analysis method from AS3995 (1) and a Dynamic Simulation procedure (7) that models the non-linear cable stays in a time history analysis using a simulated correlated wind trace (8).

2 DESCRIPTION OF MODELLING TECHNIQUES

2.1 Basic Design Approach (Static Analysis - AS3995)

The Australian Standard AS3995 provides for a basic design approach through a quasi-static analysis for along-wind loading. This analysis is based upon the application of a design regional 3-second wind gust enveloping the entire structure. The gust speed has the return period and terrain category conditions relevant to the site under consideration.

The method is considered incapable of providing an adequate assessment of the peak response conditions of particularly wind-sensitive structures (those with sufficiently low natural frequency), and as such the code specifies: "The dynamic analysis shall be undertaken for those towers and masts having a first mode frequency less than 1 Hz." {AS3995 (1) pg13 Clause 2.1}. However, the code also specifies that its procedure for along-wind response is not applicable to guyed masts, for which "a simplified approach is given in Davenport and Sparling ...." {AS3995 (1) pg26 Clause 2.3.5.1}

2.2 Simplified Method (Dynamic Analysis)

The reference for a simplified approach given in Davenport and Sparling (2) actually distinguishes two methods of performing a dynamic analysis for a guyed mast: a Simplified Statistical procedure and a Patch load method that is attributed to these authors (4,5,6).

2.2.1 Statistical Procedure

This method involves utilising the statistical properties of the wind and considers the mast response in each significant vibration mode. As a simplification of the more rigorous modal dynamic approach it treats the analysis of the response in distinct parts. Fig. 1 illustrates how the typical response spectrum for a guyed mast is split into a low frequency broad banded background component, and a series of concentrated high frequency resonant components.

Thus for design purposes, the peak dynamic response, $\hat{r}$ can be expressed in the following way,

$$\hat{r} = \bar{r} + g\tilde{r} \qquad (1)$$

in which $\bar{r}$ is the mean or time average response, $\tilde{r}$ is the rms of the fluctuating response, and g is a statistical peak factor, generally in the range of 3 to 4.

The total mean square fluctuating response can be calculated as the sum of the background response plus the contribution from each significant vibration mode,

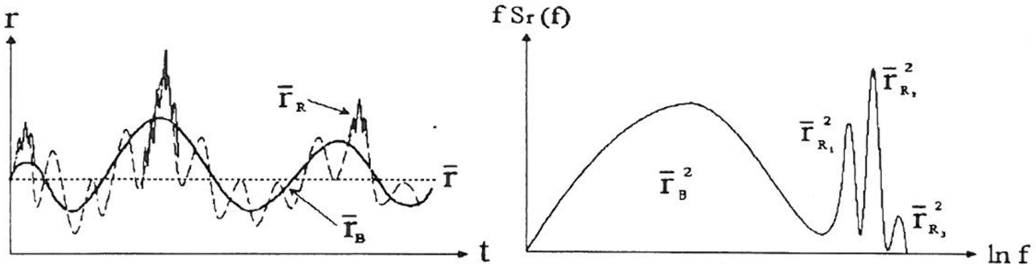

Figure 1 Typical Response of a Guyed Mast to Wind (a) Time History, (b) Spectrum of Response

$$\tilde{r} = \sqrt{\tilde{r}_B^{\ 2} + \Sigma\, \tilde{r}_{Rj}^{\ 2}} \tag{2}$$

Here, $\tilde{r}_B$ is the rms background response and $\tilde{r}_{Rj}$ is the rms resonant response in the j-th mode of vibration.

The background response occurs at frequencies below those at which dynamic amplification effects are significant. It can thus be treated in a quasi-static manner; the response of a static structure subject to a random load. The resonant component of the dynamic analysis must still be calculated using modal analysis with the only part of the forcing spectrum now needed to be considered being in the regions of the natural frequencies of the structure.

The modelling methodology for estimating the dynamic response is to treat the mast as an elastic beam, (for the mast), supported by non-linear springs, (for the cables). The horizontal stiffness of the guy clusters needs to be evaluated for the design mean wind condition associated with the particular cable-stayed mast under consideration. Because the force-displacement characteristics of the guys are non-linear, iterative techniques are adopted in mast design programs to solve for the required cable parameters (cross-sectional area and initial pre-tension) necessary to produce a uniformly linear lean along the mast. (A more detailed explanation can be found in Haritos & Chiu (3), the relevant diagram is shown in Fig. 2.)

2.2.2 Patch Load Method

The patch load method involves using static load patterns applied to the mast in succession in order to approximate the effects of wind gusts. The response of the mast from these load patches, is scaled using factors depending on the physical properties of the mast and the nature of the wind load. The patch load method has been implemented and reviewed in Haritos and Chiu (3) and will not be discussed further in this paper.

2.3 Non-Linear Simulation Procedure

This is the only dynamic procedure implemented which determines a response time history for the structure at specified time steps dependent on a simulated correlated wind trace. The traditional stiffness method of analysis may be used to model the response of the mast structure to a time varying load, according to the dynamic equilibrium equation:

$$[M]\{\ddot{X}\} + [C]\{\dot{X}\} + [K]\{X\} = \{F(t)\} \tag{3}$$

where [M], [C], and [K] are the mass, damping, and stiffness matrices for the model used and $\{\ddot{X}\}$, $\{\dot{X}\}$, and $\{X\}$ are vectors for the accelerations, velocities, and displacements corresponding to the resultant motion in the model. $\{F(t)\}$ is the corresponding forcing vector that would apply under strong wind conditions.

The method of dealing with the non-linearity of the cables adopted in the present approach, involves treating the non-linear cable force at the connection point to the mast as part of the forcing produced on the mast itself. Thus updating and iteration are required to produce the applicable cable forcing effects at each time step, but the definition of the matrices [M], [C], and [K] are retained in their original forms. The time varying wind load is generated using an efficient, easily implemented scheme based upon an Inverse F.F.T algorithm and capable of the digital simulation of spatially separated correlated wind trace(s). Time-step-integration techniques such as Wilson's θ or Newmark's β method are often used to solve the time varying dynamic equation, with the effects of cable nonlinearities fully considered. The non-linear cable force is illustrated in Fig. 2 with its equivalent generated rms fluctuating wind.

3. APPLICATION TO AN EXISTING 203m MULTI-LEVELLED GUYED MAST

3.1 Improvement of Statistical Procedure Integration Scheme

Previous work by the authors on a suitable implementation scheme for the statistical procedure has first been demonstrated in Haritos and Chiu (3). The first trial of a working model involved using a spreadsheet approach to

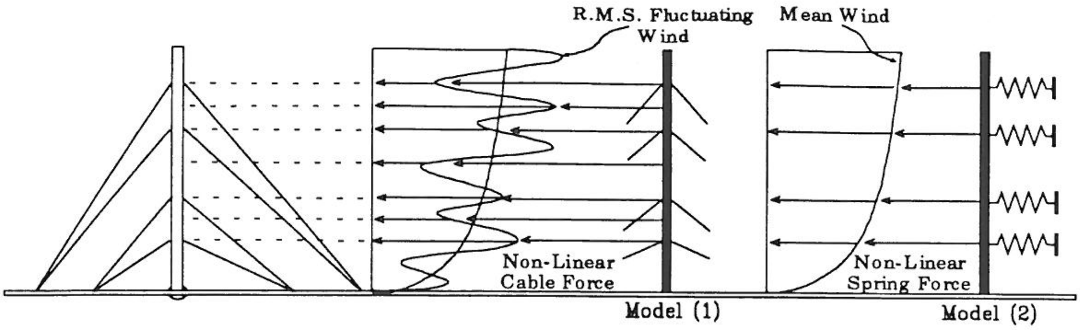

Figure 2 Multi-Levelled Guyed Mast with Dynamic Models
(1) Non-Linear Simulation Method, (2) Simplified Statistical Method

approximate the integrations of the influence lines and mode shapes. Utilising the simple functions of a spreadsheet leads to a trapezoidal summation of the integration components:

$$\int f(z)dz \cong \sum_i f(z_i)dz \tag{4}$$

The next step in optimising the model, was to trial a more efficient integration procedure. The 1/3 Simpson Rule was chosen as the most effective and easy to implement integration scheme, which could be simply used in a spreadsheet:

$$\int f(z)dz \cong \sum_n \left(f(z_0)+f(z_n)+4f(z_{odd})+2f(z_{even})\right)dz/3 \tag{5}$$

This optimisation has lead to the following results in the total moment calculated at the end of the statistical procedure. A comparison of the two integration schemes, and the relevant number of node points each scheme needs to provide an accurate prediction is illustrated in Fig. 3.

The results in Fig. 3 demonstrate that for the basic summation procedure of integration, a minimum of 4 nodes between each span is necessary for an accurate estimation of midspan moments, as the 2 node method overestimates the total moment. However, using the Simpson's Rule integration procedure, even with just 2 nodes between each span, the calculated midspan moments are more accurate than when using the 4 node simple summation procedure.

3.2 Comparison of Simplified Statistical and Non-Linear Simulation Methods

The bending moments acting on an existing 203m multi-levelled guyed mast were determined using both the Simplified Statistical and Non-Linear Time History Response Simulation methods. The Statistical procedure yielded a single set of results for a specified design mean wind as per the Dynamic Analysis section AS3995. The Non-Linear Simulation method however, was able to determine a range of values depending on the length of wind load trace applied. A 5 minute time history was chosen which was dependent on available computer resources. An Upcrossing statistical procedure using a Weibull distribution function was used in predicting the maximum response in a 1 hour storm, from a single realisation of the simulated 5 minute random wind load applied to the structure.

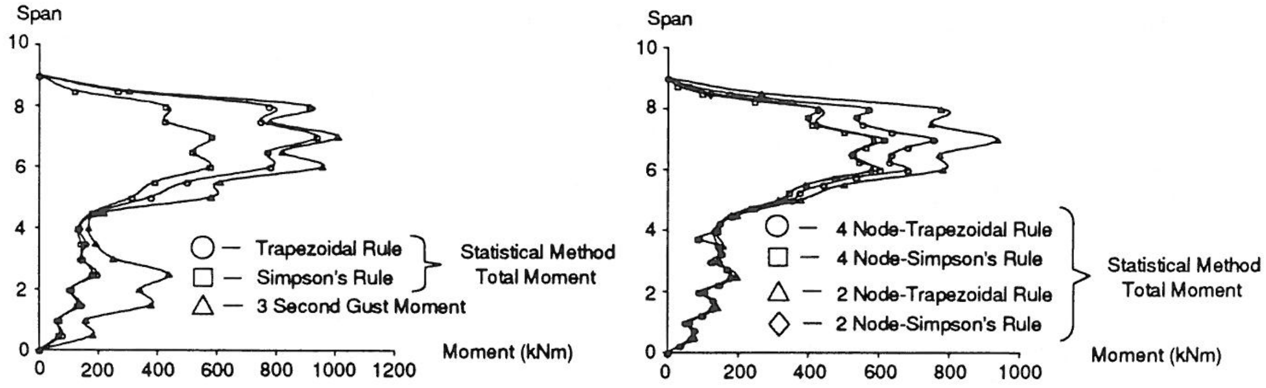

Figure 3 Comparison of Integration Schemes Implemented into the Spreadsheet

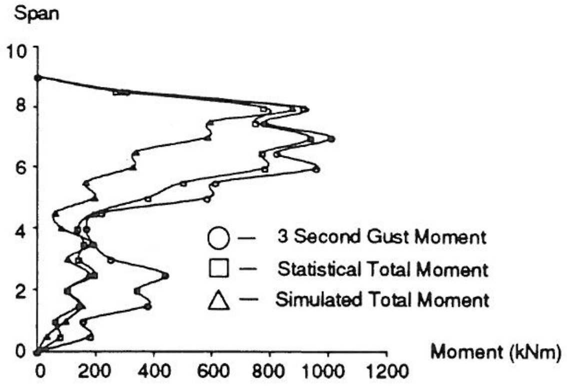

Figure 4 Comparison of Dynamic Response Methods

The comparison of the two dynamic analysis methods is depicted graphically in Fig. 4 against the results from the 3 second gust static design procedure of AS3995 (1). Both dynamic procedures demonstrate that the Static Design method of the code is conservative in its response estimation. It is also apparent that the Simplified Statistical procedure is more conservative in its estimation of the maximum bending moment that acts on the structure. The difference in the position of the maximum moment is due to the dependence of the Static Analysis and Simplified Statistical methods on the modal contributions and in the manner in which the wind loading is correlated on the structure. The simulation method allows the structure to be loaded in accordance with a simulated wind load (8), separated and correlated with height, and does not infer the manner in which modes are combined.

4 CONCLUSION

The results of the optimisation of the Statistical dynamic analysis illustrates that Simpson's Rule is a far more efficient method of integration even when the discretisation of the mast is very coarse. Although the use of Simpson's rule may be more time consuming to implement than the direct, easy-to-use spreadsheet summation commands, the results obtained are far more accurate, and this expenditure of time is thus rewarded.

Comparisons of the predictions from the three dynamic response methods yielded results which demonstrated the conservatism of the basic design approach. However, the results of the Non-Linear simulation method whilst comparable to those obtained by the method of Davenport and Sparling suggest the maximum response to be in the segment adjacent to that for the maximum load in this method.

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