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Wind Loads on a Lighting Tower

L. W. APPERLEY and K. C. S. KWOK

School of Civil and Mining Engineering, University of Sydney.

ABSTRACT

Following acceleration measurements at the top of a 70 m lighting tower at the Sydney Cricket Ground displacements of the top of the tower have been calculated using a digital double integration technique. The results presented show that for the cases considered the displacements due to the resonant response of the tower are significantly less than those produced by low frequency fluctuations in the wind flow.

The calculated displacements were found to be particularly sensitive to long period trends in the measured acceleration signal, as the double integration over the record period results in a net displacement from such offsets. These trends may be real or a result of equipment characteristics, and it was found essential to remove these components of the signal before analysis.

By the use of suitable processing techniques, the method is shown to be suitable for the calculation of relative displacements of structures.

INTRODUCTION

The Sydney Cricket Ground (S.C.G.) Lighting Towers were installed in 1979 to fulfill illumination requirements for night cricket. The six individual towers are spaced evenly around the Cricket Ground, each consisting of a tapered cylindrical steel stack 65 m high with a wall thickness varying from 10 mm at the base to 5 mm at the top (fig. 1). The head-frame is 10.2 m high and carries 70 lights. The tower is made up of cylindrical steel sections bolted together. The tower is mounted on 10 bored cast in situ piles with a reinforced concrete pile cap 6 m square and 900 mm deep and fixed to it by bolts cast into the pile cap around the base of the tower.

Following the erection of the towers an anemometer was installed on the top of one of the towers, at a height of 67 m. This is connected to a micro-computer based Data Aquisition system for the long term recording of wind data. In 1982 an intensive study was conducted into the behaviour of the tower under wind loading. This study, described by Kwok et al. (1985), and more fully by Bailey (1982), obtained records of the acceleration responses of the tower, resulting in the determination of the mode shapes and natural frequencies. The response spectra are shown in fig. 3.

The magnetic tape records obtained in this earlier study have now been analysed more closely in an effort to obtain more information on the behaviour of the tower. For example, although not presented here, the determination of displacements, together with a knowledge of mode shapes, will allow an estimate of strains and hence stresses to be obtained at any section of the structure.

INSTRUMENTATION AND MEASUREMENT

A two-component accelerometer was installed near the top of the tower at the bottom level of the headframe. The accelerometer was aligned along the two main axes of the frame, shown in figure 2. A magnetic tape recorder was installed near ground level on which the accelerometer outputs were recorded. The recorded response signals were analysed using a spectral analysis program to determine the natural frequencies of vibration and the damping levels. The spectral densities are shown in fig. 3. While measurements were in progress, the wind velocities were monitored by the anemometer. Wind speeds were generally light to moderate (less than 8 m/s). The sample period used was approximately ten minutes, this was considered to be sufficiently long for stable average values to be obtained, and to allow a suitable sample size for later later digital analysis. Longer sample periods may be desirable for a more complete determination of the displacement cycle and future measurements planned on similar structures allow for sample periods of 20-30 minutes.

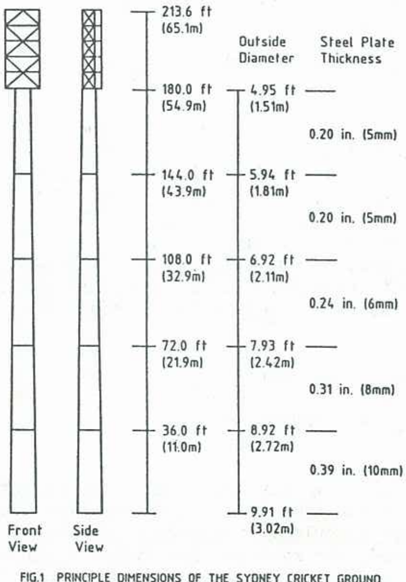

FIG.1 PRINCIPLE DIMENSIONS OF THE SYDNEY CRICKET GROUND LIGHTING TOWERS

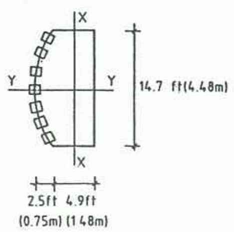

FIG.2 PLAN VIEW OF HEADFRAME SHOWING ARRANGEMENT OF LIGHTS

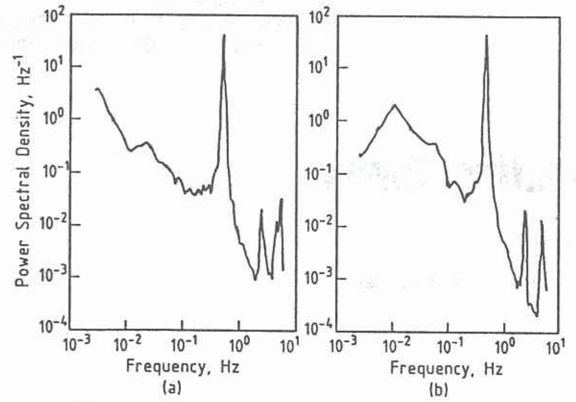

FIG.3 POWER SPECTRAL DENSITY FUNCTIONS OF ACCELERATION RESPONSES SHOWING NATURAL FREQUENCIES. (a) X-X DIRECTION; (b) Y-Y DIRECTION

DATA ANALYSIS

The data stored on magnetic tape was digitised using the equipment described above. The channels containing data for the X and Y components of acceleration were low-pass filtered at a cut-off frequency of 30 hz. This was considered a suitable value as the third mode natural frequency of 5 hz would have virtually no phase shift relative to the lower frequencies of the signal. A sample rate of 50 hz was chosen as it was considered that the higher frequencies present in the signal would be adequately reproduced. The X and Y accelerations were sampled simultaneously, with 15,000 samples of each channel, giving a sampled record time of five minutes.

The basic relationship between acceleration, velocity and displacement are

$$v_n(t) = \sum_{i=1}^{n} a_i(t).\ \Delta t + v_o$$

and $$x_n(t) = \sum_{i=1}^{n} v_i(t).\ \Delta t + v_o.n.\Delta t + x_o$$

where v_o is the initial velocity and x_o the initial displacement. Neither of these quantities are known, but if x_o is assumed equal to zero (or some convenient initial value), then displacements relative to this initial value may be calculated. The initial velocity v_o may be found by carrying out an initial integration, and, assuming the net displacement over the period of integration to be zero, the final displacement value at the end of the initial integration is

$$X_I = v_o.N.\Delta t$$

i.e. $$v_o = X_I/N.\Delta t$$

This value of v_o may now be used in the integration to obtain the true relative displacement values. A number of numerical integration techniques were considered, and results from linear interpolation methods were compared with those obtained from the familiar Simpson's Rule. No observable differences were obtained with the sample frequencies used, however it was decided to use equations based on the Simpson expression as these would lead to greater accuracy in the event of the use of a lower sampling frequency to signal frequency ratio.

Initial calculations carried out in this fashion produced some unrealistic displacements, of the order of metres in some cases. It became apparent that small overall trends in the acceleration data were producing significant false displacement values. To remove the signals with periods greater than the record period a standard trend removal procedure was used, similar to that described by Bendat and Piersol (1971). If the original data record is $\langle a_n \rangle$, n=1,2, 3.....N, then the record after trend removal is

$$\tilde{a}_n = a_n - \hat{a}_n$$

where $\hat{a}_n$ is a corrective term applied to each value of the original record to eliminate signals with periods longer than the data record. Values of $\hat{a}_n$ may be calculated in a number of ways, generally the most suitable being by a method of least squares, where polynomial expressions for $\hat{a}_n$ may be derived, and the appropriate degree of polynomial used. The general form for $\hat{a}_n$ is

$$\hat{a}_n = \sum_{j=o}^{J} k_j\ (n.\Delta t)^j \qquad \text{for } n = 1,2,3,\ldots\ldots,N$$

where the coefficients, k_j, for the degree (J) of the polynomial chosen may be determined using a least squares analysis, from the J+1 equations of the form

$$\sum_{j=o}^{J} k_j \sum_{n=1}^{N} (n.\Delta t)^{j+\ell} = \sum_{n=1}^{N} a_n (n.\Delta t)^{\ell} \qquad \text{for } \ell=0,1,2,\ldots,J$$

A 2nd order polynomial was chosen for the data analysis in this study, since this would eliminate both linear trends due to instrumentation characteristics, e.g. (drift) and any longer period cyclic fluctuations produced by wind velocity variations.

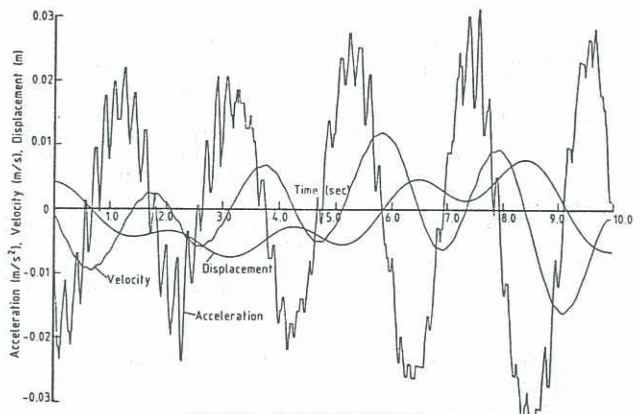

FIG.4 TYPICAL TOWER RESPONSE (X-DIRECTION)

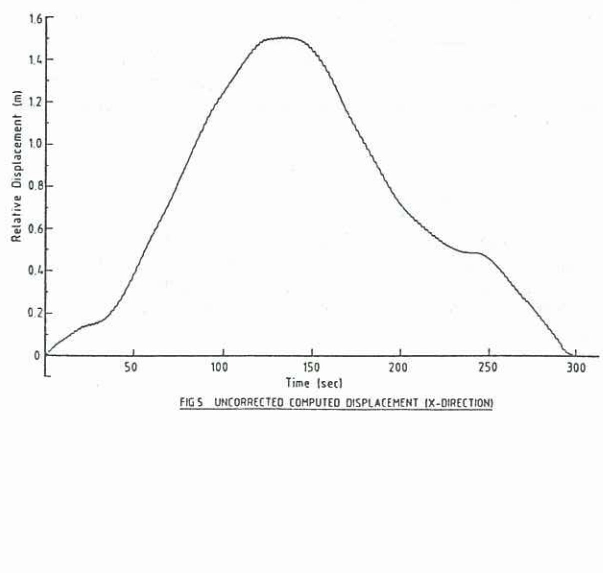

FIG.5 UNCORRECTED COMPUTED DISPLACEMENT (X-DIRECTION)

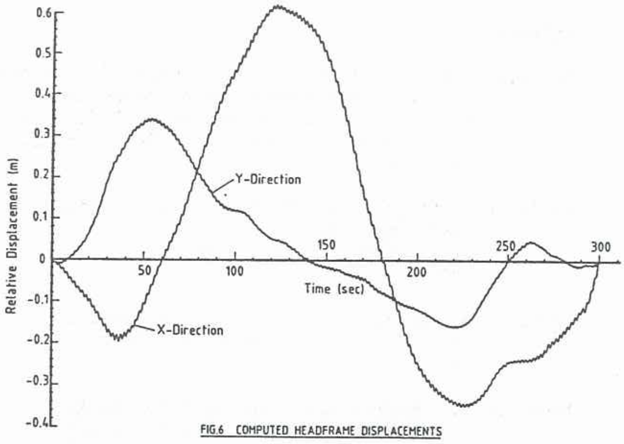

FIG.6 COMPUTED HEADFRAME DISPLACEMENTS

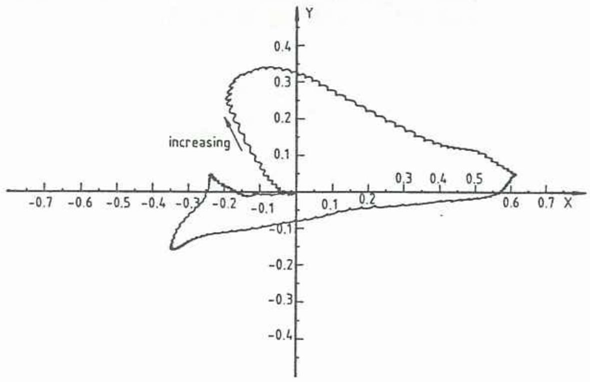

FIG.7 DISPLACEMENT OF HEADFRAME (m) OVER 5 MINUTE PERIOD

The coefficients $k_0 \ldots k_2$ were obtained from the following equations:-

$$k_0.N.\Delta t + k_1 \sum_{n=1}^{N} (n.\Delta t) + k_2 \sum_{n=1}^{N} (n\Delta t)^2 = N.\Delta t \sum_{n=1}^{N} a_n$$

$$k_0 \sum_{n=1}^{N} (n.\Delta t) + k_1 \sum_{n=1}^{N} (n.\Delta t)^2 + k_2 \sum_{n=1}^{N} (n\Delta t)^3 = \sum_{n=1}^{N} a_n.(n.\Delta t)$$

$$k_0 \sum_{n=1}^{N} (n.\Delta t)^2 + k_1 \sum_{n=1}^{N} (n.\Delta t)^3 + k_2 \sum_{n=1}^{N} (n.\Delta t)^4 = \sum_{n=1}^{N} a_n(n\Delta t)^2$$

The effect of this trend removal is illustrated in figs. 5-6. Fig. 5 shows the computed displacements for the X-direction of the headframe using the uncorrected acceleration values. A displacement of approximately 1.5 m results compared with approximately 0.9 m for the displacements calculated from the corrected record. The Y-direction accelerometer produced even greater differences, the most likely reason being a larger drift component in the transducer amplifier.

RESULTS

The acceleration record for a wind speed of 7.8 m/s was chosen for analysis, as it was at the upper speed range of records available, and included acceleration components from both the first and third modes of vibration. Fig. 4 shows the results from a typical segment of that record. It is of interest to note that whilst significant third mode oscillations are present in the acceleration signal their contributions to both the velocity and particularly displacement are minimal. The range of displacements over the 10 second period of the record is approximately $\pm$8mm, with velocities from -0.016 to +0.012 m/s, and accelerations from -0.034 to +0.031 m/s², (0.35% g).

Initial expectations were that the displacements would essentially follow the trend of those shown in fig. 4 i.e. a cyclic variation with a frequency equal to that of the fundamental mode. However, it became apparent that much longer period components existed in the acceleration signal response, those due to wind velocity variations. The displacementes shown in fig. 6 clearly show that, for this particular structure under the observed loading conditions, the displacements due to oscillations at the fundamental frequency contribute only a very small percentage of the overall displacement. The displacements are dominated by the wind velocity fluctuations. In fig. 3 the spectral densities of the acceleration responses show peaks at periods in the range 150-200 sec., which closely correspond to the periods of the displacement curves. A power spectral analysis is not available for the wind record during the tests, however, an analysis of the spectral density of wind speeds over a similar terrain category show a peak at similar values of reduced frequency as those present in the acceleration signal [Apperley and Pitsis(1985)].

It should be noted that all calculated displacements are relative to the displacement at the beginning of the analysis and the net displacement over the period of integration is assumed to be zero. Hence the displacement record to some extent will be dependent on the sample period. It is necessary to use a zero net displacement in order to obtain the initial velocity v_0, however it may possible to carry out an initial integration on the record to find the occurrence of maximum velocity corresponding to the location of zero displacement, and adjust the displacement record accordingly. Further work is intended on this aspect together with the effect of varying sample periods.

The X and Y components of displacement plotted in fig. 6 have been combined to give the total relative displacement which is presented in fig. 7. The fundamental frequency oscillations are still discernable, and the overall movement of the headframe may be observed over the 5-minute sample period.

CONCLUSIONS

Analysis of acceleration records of the headframe of a lighting tower using a double-integration technique has shown that

(1) Relative displacements of the headframe can be obtained from these records.

(2) Displacements due to resonant oscillations of the tower are small compared to the displacements produced by variations in wind velocity.

It may be noted that in view of the negligible effect on the displacement of the higher order modes of vibration, a much lower sample frequency than used in the present study may be employed, resulting in fewer calculations or the use of a longer sample period.

Nomenclature

Variables

N - sample size

X,Y - mutually perpendicular axes as defined in fig. 2.

Greek Symbols

Δt - sample time interval

Subscripted variables

$a_i(t)$ - the ith value of the acceleration variable in the series i = 1,.....N

a_n - the nth data value in the uncorrected acceleration record

$\hat{a}_n$ - the corrective term applied to a_n

$\tilde{a}_n$ - the nth value of the corrected acceleration record

$k_o.....k_j$ - coefficients of the jth order corrective polynomial

v_o - initial velocity at i = o

$v_n(t)$ - the nth value of the velocity n = 1,....N

X_I - calculated displacement at the end of the initial integration

$x_n(t)$ - the nth value of the displacement n = 1,....N

References

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