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A RELIABILITY STUDY OF WIND TUNNEL RESULTS FOR CLADDING PRESSURES

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Abstract

Load Factors or Safety Factors applicable to wind tunnel results of cladding pressures are presented. These incorporate the effect of method of analysis, the digitisation process and a number of sampling parameters. The sampling parameters investigated were the sample length, the sampling frequency and the low-pass filtering frequency. In the process of assessing the effect of these parameters, a number of methods of analysis were compared in terms of their sensitivity to the sampling parameters and the digitisation process.

1. INTRODUCTION

Wind tunnel testing is now considered a well established method of predicting wind pressures on cladding for the design of cladding panels and their fixtures. However, few systematic studies have been undertaken on the reliability of wind tunnel results of wind pressures on cladding. The first such studies were by Davenport [1,2] and Holmes [3]. This study is essentially a continuation of the above, with a minimum of overlap. The aim of this study is to investigate the effect of the various methods of analysis on the Peak Factors obtained from wind tunnel pressure results. The different methods of analysis are also compared in terms of their sensitivity to a number of sampling parameters and the digitisation process. The effect of the various sampling parameters on the reliability of the wind tunnel cladding pressure results has not been studied before. The sampling parameters investigated are the sample length, sampling frequency and the low-pass filtering frequency of the pressure signal. The study concludes with a set of Load Factors (or Safety Factors) applicable to wind tunnel results of cladding pressures for each method of analysis. The Load Factors that were computed were based on results of this sensitivity study, together with the effects of other parameters suggested by Davenport [1,2] and Holmes [3].

Five methods of analysis have been investigated in this study. These are the Largest Peak method, the Direct Extreme Value Analysis (DEVA), the Upcrossing method (both the Standard Upcrossing method and an alternative, semi-empirical Upcrossing method), Peterka's method [4] and a Peak Distribution method developed recently by Melbourne and Cheung [5]. Only a brief description of each method will be given in this paper. All results of peak pressure analyses were converted into Peak Factors (standard deviations from the mean) for comparison.

The Largest Peak method is where one simply treats the largest peak occurring over a sampling time of one hour as the estimated mean hourly peak pressure. The DEVA, which is the most commonly used method, was investigated using Gumbel's method as well as the methods of Lieblien [6] and Gringorten [7] for correction of the bias due to the ranking process. An Alternative DEVA, developed by the authors, was also compared with Gumbel's DEVA in terms of sample length requirements. The Alternative DEVA directly analyses the distribution of consecutive extremes instead of using order statistics (hence not requiring correction for bias).

The Standard Upcrossing method (or more correctly, the Normalised Crossing method), has been reported by Melbourne [8]. In this method the pressure range is divided into small bands. The data consists of the number of crossings with positive slope made by the signal at different levels of pressure. The data is used to determine the pressure distribution. The peak pressure is then derived from Fisher Tippett Type I parameters. The Alternative Upcrossing method differs from the Standard Upcrossing method in that the peak pressure corresponds to a crossing rate of an empirically determined fraction of the crossing rate at the mean value of the fluctuating pressure signal.

Peterka's method consists of selecting the 100 largest independent peaks occurring in a one hour sample and analysing them using a Gumbel distribution function. Peterka [4] recommended using averages of 2 or 4 hours by averaging the results of separate one hour records. The possibility of using Peterka's method for single records of different durations, ranging from 15 minutes to 4 hours was investigated.

In the Peak Distribution method, a Weibull distribution is fitted to all the peaks occurring in a 2 to 3 hour interval. In this investigation; sample lengths in the range of 15 minutes to 4 hours were investigated. The suitability of the Poisson distribution function for fitting the data was also investigated.

2. EXPERIMENTAL SETUP

A perspex CAARC model of 1:500 scale was used. The actual dimensions, of the model were 360 x 60 x 90 mm. It was tested in a 1:500 scale category 2 (open country terrain) wind model. The test was conducted at the University of Sydney No.1 Boundary Layer Wind Tunnel. It is of an open circuit type and its dimensions are 2.4 x 2.0 x 20 m. The augmented growth method was used to generate the wind model over a fetch length of roughness elements.

Six pressure taps were positioned as shown in Figure 1. Four signals were selected for the reliability analysis. These four signals are considered to be representative of the various types of pressure signals: Channel 0 for the windard face, Channel 0' for the leeward face, Channel 3 for the upstream edge of the side face and Channel 5 for the downstream edge of the side face. The taps were at 2/3 of the building height. The standard deviations of the wind pressure fluctuations at these positions were sufficiently large to allow the results to be presented in terms of Peak Factors.

The pressure measurement system was based on the leak tube system described by Gerstoft and Hansen [9]. The purpose of the leak tubes was to attenuate resonant peaks in the response of the system. The system was calibrated by using the method reported by Holmes and Lewis [10]. The leak tube pressure measurement system had a flat response (to within 10 percent) to ~300 Hz and had no resonant peaks up to about 1000 Hz.

The pressure signal output was initially recorded on tape by a frequency modulated data recorder which has a frequency response up to 1250 Hz. The recording of the signal on tape allows one to investigate the effect of the various sampling parameters and methods of analysis of the peaks without changing the actual signal. The signal was initially filtered at 1000 Hz so as to allow the effect of filtering frequencies to be investigated both within and beyond the range of the frequency response of the pressure measurement system. The digitised data were stored on disk. This would omit discrepencies due to uncertainties up to the digitisation stage.

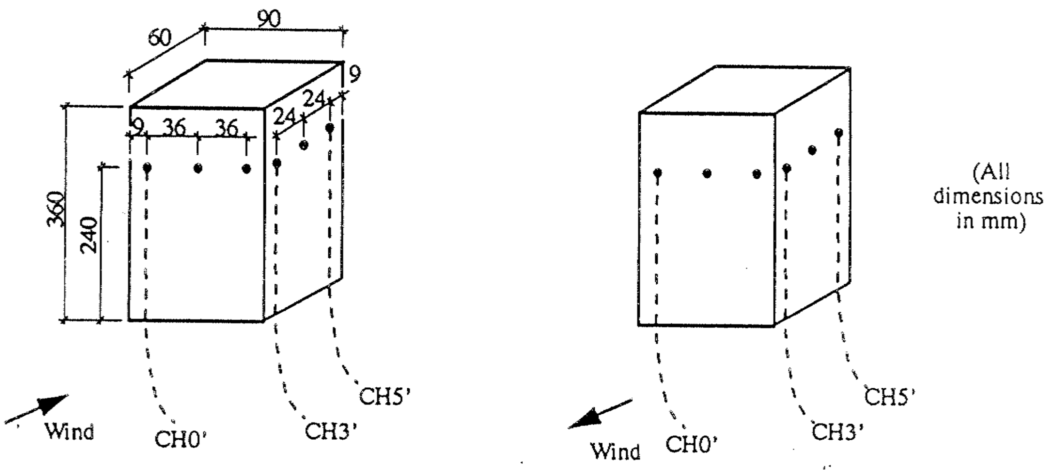

FIG.1 LAYOUT OF PRESSURE TAPS ON THE BUILDING MODEL

3. COMPUTATION OF LOAD FACTORS

Davenport [1,2] suggested a method of error analysis for wind tunnel results based on the second moment reliability method. In determining a suitable safety factor for cladding pressures, Davenport [2] has incorporated the uncertainties in the reference wind velocities in the model and the prototype, in addition to uncertainties in the predicted pressure difference (which includes the effect of uncertainties in the internal pressure and the effect of repeatability of the estimate of the peak pressures) as well as uncertainties in the peak factor, method of analysis and in changes in the exposure. All these have significant effects on the reliability. They add up to a Load Factor (or "safety factor") of 1.84, assuming a safety index of 3.0. Holmes [3] has made similar estimates of the effects of these factors with the exception of the effect of the repeatability of the pressure difference and has included the effect of the velocity multiplier for the upstream terrain and the air density among the factors affecting the wind tunnel results for cladding pressures. However, these extra factors had only a very slight effect on the reliability. The uncertainies suggested by Davenport [2] and Holmes [3] which relate to wind tunnel predictions of cladding pressures are summarised in Table 1, together with those suggested by the authors.

In this analysis, the method of predicting the repeatability of the peak pressures is quite different to that presented by Davenport [2]. In this study, the repeatability parameter is dependent upon a number of factors. These are the digitisation process, the sample length, sampling frequency and filtering frequency. These parameters vary with the various methods of analysis investigated in this paper. The various factors have been incorporated into the

Load Factors using the second moment reliability method adopted by Davenport [1,2].

TABLE 1

A COMPARISON OF ASSUMED LEVELS OF UNCERTAINTIES

Factor	DAVENPORT (1983) Phi	COV	HOLMES (1985) Phi	COV	SUGGESTED VALUES Phi	COV
Changes in upstream conditions	1.0	0.10	0.8	0.10	0.9	0.10
Effect of openings in walls and roof on the internal pressure	1.0	0.05	1.0	0.05	1.0	0.05
Wind tunnel modelling of the wind and building	1.0	0.10	1.0	0.10	1.0	0.10
Repeatability in the predicted pressure difference	1.0	0.19#	--	--	1.0	0.25~
Analytical modelling of local pressure factors (e.g. stationarity)	1.0	0.05	1.0	0.05	Included in the above.	
Meteorological estimates of wind velocity	1.0	0.10	1.0	0.11*	1.0	0.11
Velocity multiplier for upstream terrain	--	--	1.0	0.05	1.0	0.05
The density of air.	--	--	1.0	0.02	1.0	0.02

Notes: # This is based on a value of 0.17 for the mean, combined with a factor of 0.08 for the prediction of the gust factor.

~ Based on experimental work by the author. The corresponding value for the Largest peak method is 0.35.

* This is based on a value of 0.09 for the C.O.V. of the actual data, combined with an allowance of 0.06 for sampling errors.

4. RESULTS AND DISCUSSION

The following sections summarise the effects of the various parameters affecting the pressure results obtained from wind tunnels. Results are presented in terms of the average variation expressed as a factor, φ, and the dispersion from the average variation (within a 95 percent confidence limit), expressed in terms of a Coefficient of Variation. Positive percentage variations indicate that the values are more conservative. In the last part of this section Load Factors are presented for each method of analysis. These Load Factors incorporate the uncertainties of all the parameters studied in this paper in addition to the suggested uncertainties due to other parameters given in Table 1.

4.1 Effect of Non-Stationarity and the Digitisation Process

The combined effect of non-stationarity and the digitisation process on the digitised signal was investigated by analysing the pressure signals obtained from 215 pressure tap locations on a medium-sized multi-storey building model. The combined effect was investigated due to the difficulty in assessing the effect of each factor separately. The test was repeated once with exactly the same settings and wind characteristics. The results presented here are based on a sampling frequency of 1000 Hz and a low-pass filtering frequency of 300 Hz. These values of the sampling and low-pass filtering frequencies were treated as the reference values when investigating the effects of sampling and low-pass filtering frequencies. Figure 2 presents the distribution of the variation parameters for maximum and minimum pressure coefficients. The measured mean, standard deviation, maximum and minimum pressure ranges were divided into C_p intervals of 0.05. φ and Coefficients of Variation (COV) were determined at each C_p level and are based on all the peaks with values of C_p greater than that level. The variation parameters are based on a minimum of 10 values. The value of φ for the mean and standard deviation of the fluctuating signal was approximately 1.0, that is virtually no change. The value of the COV was 0.10 for the mean and 0.08 for the standard deviation.

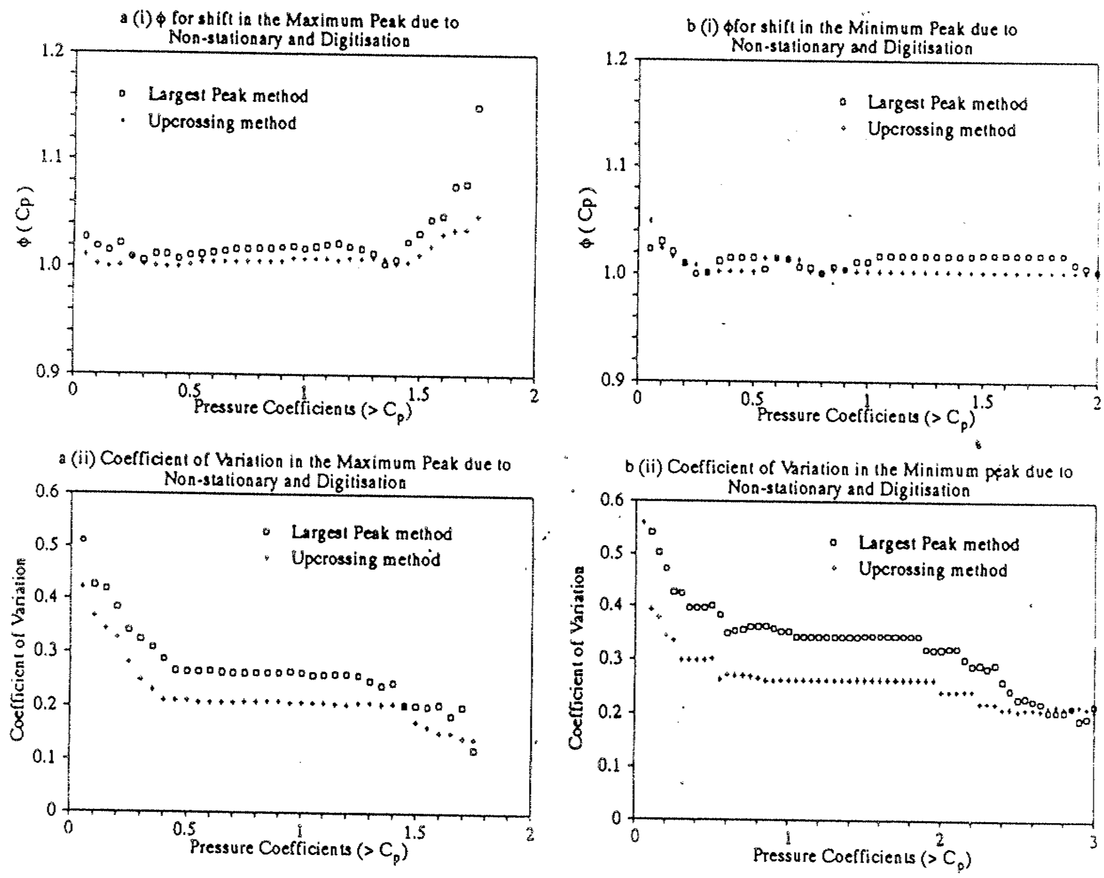

FIG.2 THE EFFECT OF NON-STATIONARY AND DIGITISATION PROCESS

The distributions of φ and the COV for the peak pressures can be divided into three regions. These are regions of small C_p ($C_{\hat{p}}$>−0.5 or $C_{\hat{p}}$<+0.5), intermediate C_p and large C_p ($C_{\check{p}}$<−2.1 or $C_{\hat{p}}$>+1.4). Values of φ and the COV for the peak pressures, to be discussed, are based on the intermediate region, where the values of φ and COV are almost uniform. The reason for neglecting the large values of the variation parameters for the peak pressures of small magnitude is that the variation in small peak pressures become significant only in relation to the magnitudes of the peak pressure coefficients. The reason for the large increases in φ and reductions in the Coefficients of Variation at $C_{\hat{p}}$ greater than +1.4 in the positive peaks and $C_{\check{p}}$ less than −2.1 in the negative peaks is that the number of occurrences in these ranges begin to diminish.

The COV for the maximum and minimum peaks derived using the Alternative Upcrossing method were significantly lower than the COV for peaks obtained using the Largest Peak method. It can be seen in Figure 2(ii) that the COV for the maximum peaks, $C_{\hat{p}}$ > +0.5 was reduced from 0.25 to 0.20 when the Upcrossing analysis was used. For the minimum peaks, the reductions in the COV were even more pronounced. Figure 2(iv) shows the effect of the Upcrossing analysis in reducing the COV for the minimum peaks, $C_{\check{p}}$ < −0.5, from 0.35 in the Largest Peak method to 0.25 for the Upcrossing method. The effect of the Upcrossing method in improving the repeatability of the results obtained after digitisation is mainly due to its dependance on the parent distribution rather than a single peak. The fact that the reductions in the COV was greatest for the minimum pressures was expected since unusually high or sharp intermittent peaks occur only in the negative pressures [11]. In computing Load Factors for the other methods of analysis it was assumed that the Alternative Upcrossing method is sufficiently representative of methods involving curve-fitting of the data. Hence the effect of non-stationarity and the digitisation technique for the other methods would be similar to that of the Alternative Upcrossing method, with φ = 1 and COV = 0.25.

4.2 Effect of Sample Length

In this study, the length ratio was 1:500. For a velocity ratio of approximately 1:3, the time ratio becomes 0.006. This means that 1 hour in the prototype is equivalent to approximately 20 seconds in the wind tunnel.

The effect of sample length on peak pressure results obtained using Gumbel's DEVA, the Alternative DEVA, Peterka's method, the Peak Distribution method and the Standard and Alternative Upcrossing methods was investigated. Since by definition, the Largest Peak method is based on a fixed record length of 1 hour and does not relate the peak to any particular probability level or reference record length, no comparison can be made for this method. The two types of DEVA were tested for sets of 8, 16, 32, 64 and 100 records, each of 15 minutes duration in the prototype. The remaining methods were tested for sample lengths between 15 minutes and 4 hours. The results of the effect of sample length are summarised in Figures 3(i) to 3(iv).

The results shown in Figure 3(i) indicate that for various types of DEVA, the errors with respect to the results obtained by using sets of 100 records increased consistently with decreasing numbers of records. It is noted that the error levels for 16 records using the Alternative DEVA were comparable to those for 32 records using Gumbel's DEVA. This suggests that the Alternative DEVA can achieve the same accuracy using half the sample length.

Errors with respect to 4 hour sample lengths, associated with the Upcrossing methods, Peak Distribution methods and Peterka's method followed a similar trend as can be seen in Figures 3(ii) to 3(iv) with the mean errors being roughly inversely proportional to the sample size. In addition to investigating

Peterka's method [4] for averages of up to 4 single hour records, the possibility of using single records of 15 minutes, 30 minutes, 1 hour, 2 hour and 4 hour duration (after converting to hourly peaks) was also investigated. Although this approach has not been investigated by Peterka, it was interesting to see that the results obtained using these smaller sample lengths showed quite small variations from the averages of the four 1 hour estimates, as shown in Figure 3(iii).

It is noted that for the Standard and the Alternative Upcrossing methods and the Peak Distribution method (using a Poisson distribution), the sample length can be reduced to 30 minutes without significantly affecting the uncertainties. For the remaining methods (with the exception of the various types of DEVA) a 1 hour sample seems sufficient.

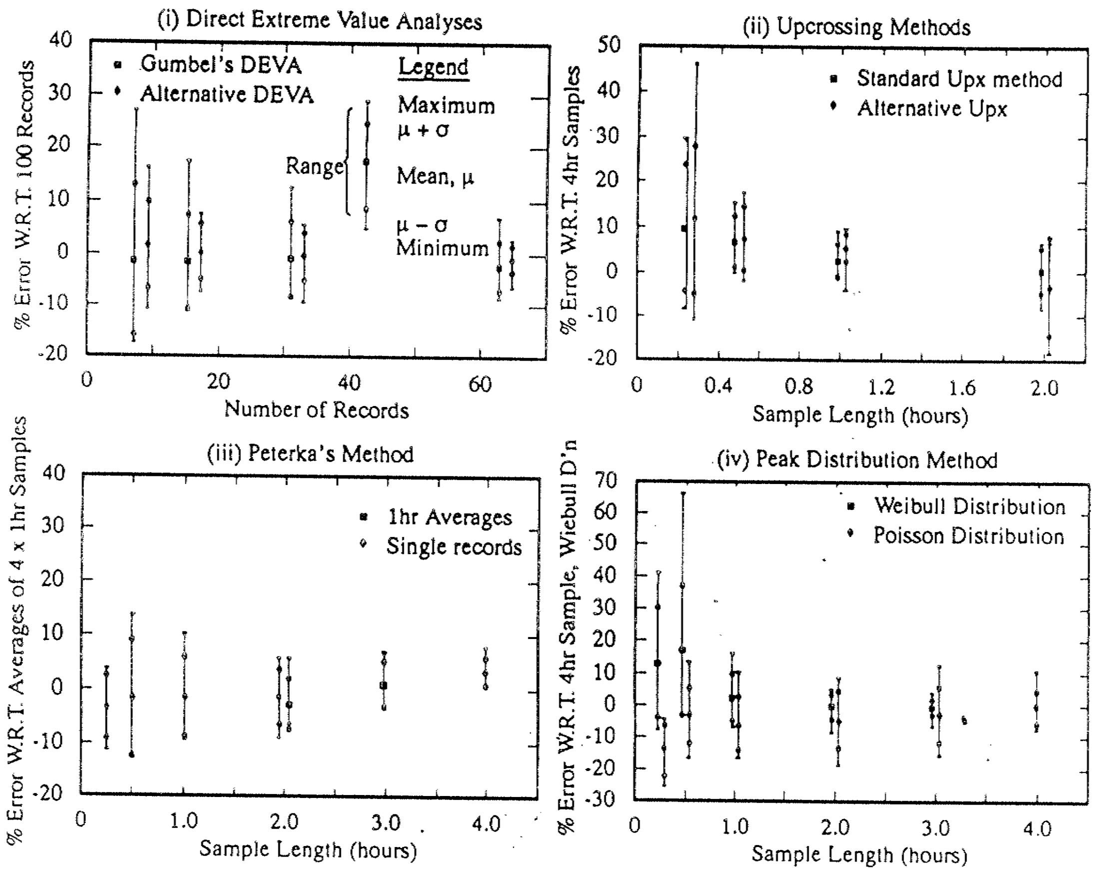

FIG.3 THE EFFECT OF SAMPLE LENGTH

4.3 Effect of Sampling and Low-Pass Filtering Frequencies

The Standard Upcrossing method, the Alternative Upcrossing method, the Largest Peak method, Peterka's method and the Peak Distribution method were applied to 1 hour samples for a range of sampling and filtering frequencies. The sampling frequencies ranged ranged from 10 to 3000 Hz and for the filtering frequencies in the range of 10 to 1000 Hz. The various types of DEVA were investigated for sampling frequencies of 1000 and 8000 Hz using a filtering frequency of 1000 Hz.

It was found that the sampling frequency and the low-pass filtering frequency were not independent variables. As the filtering frequency was increased, the sampling frequency became more critical. The higher the sampling frequency, the lesser the effect of filtering frequency, provided that the filtering frequency is within the frequency response of the system. For a fixed low-pass filtering frequency, the Peak Factors began to differ significantly as the sampling frequency went below a certain level. In Gumbel's DEVA, when the sampling frequency was reduced from 8000 to 1000 Hz the Peak Factors varied by 0 to -11 percent, with an average of -6 percent with a Coefficient of Variation (COV) of 0.03. In the Alternative DEVA the corresponding percentage variations were within the same range, with an average of -4 percent and a COV of 0.03.

For the Largest Peak method, both Upcrossing methods and Peterka's method, the variation with respect to the 1000 Hz sampling frequency followed a distinct pattern. For all methods, the variations increased more rapidly as the sampling frequency was reduced. For example, for a signal that was low-pass filtered at 300 Hz, the average variation for a 500 Hz sampling frequency was -1 percent with a COV of 0.03. Lowering the sampling frequency to 300 Hz resulted in a significant increase in the variation to an average of -5 percent with a COV of 0.03. For a 100 Hz sampling frequency, the average variation was only slightly increased but the COV was as large as 0.15. The variations arising from sampling frequencies less than 100 Hz were considerable. Hence sampling frequencies less than 100 Hz are not recommended.

In the Peak Distribution method the sampling frequency had a much more significant effect on the results than in the other methods, as a result of the method of selection of peaks (see Figure 4). For example, if a peak did not qualify because it was larger than only one digit value on either side, the same peak would qualify if the sampling frequency was doubled. Unfortunately, this tends to happen only with very small peaks near the mean. The effect of this is that the probabilities of exceedance for the different pressure levels become too low, causing the Peak Factors to be underestimated. In contrast, higher sampling frequencies in the other methods serve only to represent the pressure signal more accurately. Hence in addition to the lower limit, an upper limit of around 1000 Hz for the sampling frequency is recommended when using the Peak Distribution method.

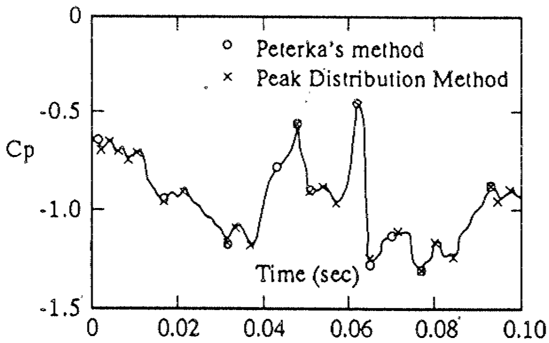

FIG.4 AN EXAMPLE OF THE METHOD OF SELECTION OF PEAKS BY THE PROGRAM PEAKS.BAS

(The figure is for the first 0.1 seconds of the Record P5RL3B)

The effect of filtering frequency was investigated for the various methods of analysis with the exception of the various types of DEVA. All the methods investigated showed similar trends. In most cases, for filtering frequencies below 100 Hz the values of the Peak Factors began to differ significantly from results based on the reference value of 300 Hz which matches the frequency response of the pressure measurement system used. Hence filtering frequencies below 100 Hz were found to be quite unacceptable for pressure tests. Other pressure measuring systems would have different effects, since the frequency response would be different to that of the system used for this study, particularly when there are significant resonant peaks at the higher frequencies. However, it can be concluded that pressure measuring systems with a frequency response of less than 100 Hz are quite unacceptable.

4.4 Effect of the Various Methods of Analysis

The effects of the various methods of analysis and of the various distribution functions was investigated. The results obtained using the various methods of analysis were derived from the same digitised data of 4 hours duration. The sampling and filtering frequencies were both set at 1000 Hz. The averages of four Peak Factors obtained by the Largest Peak method using sample lengths of 1 hour each (a total of 4 hours) was selected as an arbitrary reference value. In using the Largest Peak method, the criterion used by Melbourne and Cheung [5] for an acceptable peak was adopted. The various types of DEVA were compared using sets of 16 consecutive extremes. The types of DEVA that were compared were Gumbel's DEVA with the optional bias correction procedures of Gringorten and Lieblein, as well as the Alternative DEVA using the Gumbel, Weibull and Poisson Distribution functions. The sets of 16 extreme values were derived from digitised data of the same continuous 4 hour signals which were divided into 16 lots of 15 minute samples. The results from Peterka's method are the averages of four 1 hour peak factors, also using the same digitised signal.

The different methods of analysis produced consistent estimations of the peak pressures provided that the appropriate probability levels are used. The various types of DEVA (using $\hat{P} = U + 1.4/a$), the Upcrossing methods (at $\hat{P} = U + 1.4/a$ for the Standard Upcrossing method and a crossing rate of 1/360 for the Alternative Upcrossing method), Peterka's method, and the Peak Distribution method (using a probability level of 0.002) all gave peak factors that were within ±7 percent of the average of four peak factors obtained from four consecutive one hour records using the Largest Peak method. Gringorten's method for correction for bias in Gumbel's DEVA generally resulted in slightly larger variations from the Largest Peak method. Peterka's method gave slightly lower pressures. The Standard Upcrossing method gave the closest values to those of the Largest Peak method, being generally within 2 percent of the averages of the Largest Peak method.

4.5 Load Factors for use with Wind Tunnel Cladding Pressure Results

Plots of the computed Load Factors for the various methods of analysis are presented in Figure 5. The Load Factors are plotted with respect to the sampling and filtering frequencies since they are the most commonly varied sampling parameters. The shaded regions indicate that the settings of the sampling and low-pass filtering frequencies are unacceptable. It should be pointed out that these Load Factors are based on 95 percent confidence intervals, which may be quite conservative [1]. However, they are useful at least for the purpose of comparing the different methods. The variation parameters, φ and COV, for the effect of sampling and filtering frequencies are with respect to the reference values of 1000 Hz and 300 Hz, respectively and are based on 1 hour sample lengths. For the Alternative Upcrossing method and the Peak Distribution method, the results are also based on the previously suggested probability levels which produce peak factors that closely match averages of the Largest Peak method.

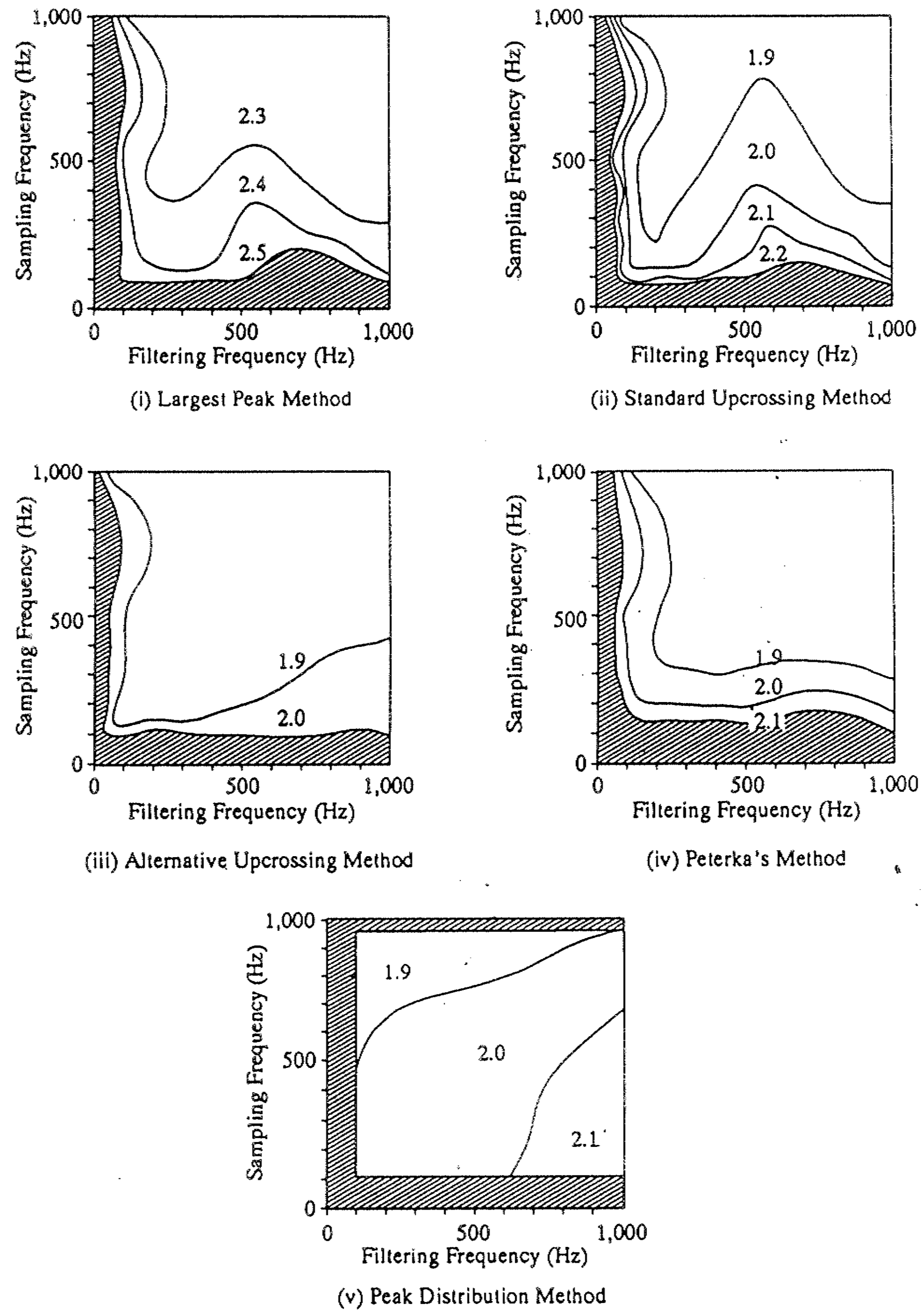

FIG.5 PLOTS OF LOAD FACTORS

Load Factors were highest, as expected, for the Largest Peak method while the Alternative Upcrossing method required the lowest Load Factors.

For the empirical methods of analysis, the effect of varying the probability level was also investigated. Values of φ and COV were obtained for variations in the peak factors with respect to the values obtained by using the suggested probability levels. It is noted that in the case of the Alternative Upcrossing method it was found that for a crossing rate of 1/3600, the values of φ and COV with respect to the suggested crossing rate of 1/360 were 0.79 and 0.03, respectively. This means that it is possible to use a crossing rate of 1/3600 (instead of 1/360) by reducing the Load Factor by a factor of 0.74 without affecting the uncertainty since the COV with respect to a 1/360 peak is only 0.03, giving typical Load Factors of between 1.41 and 1.48. However, in the Peak Distribution method the COV between peak factors based on a probability level of say 0.0001 and those based on the recommended probability level of 0.002 can be quite significant (φ is 0.59 while the COV is 0.27). Hence some allowance must be made for the large variations in computing the respective Load Factors.

With the exception of the Peak Distribution method, the Load Factors increased dramatically for sampling frequencies less that 100 Hz while the predictions consistently improved as the sampling frequencies were increased. Load factors also increased rapidly for filtering frequencies below 100 Hz. In the Peak Distribution method sampling frequencies above 1000 Hz required very high Load Factors. This is due to the method of selection of peaks which results in the selection of too many dependent peaks at the higher sampling frequencies. Hence an upper limit in the sampling frequency was set at around 1000 Hz for the Peak Distribution method.

5. CONCLUSIONS

Load factors applicable to results obtained from wind tunnel tests for cladding pressures have been derived using the method reported by Davenport [1,2]. These factors account for uncertainties in the prototype and model reference wind velocities, non-stationarity, the digitisation process, sampling and filtering frequencies as well as changes in the upstream terrain and in the internal pressures. The effect of different methods of analysis was also investigated. The methods that were compared were the Largest Peak method, the Standard Upcrossing method and an Alternative Upcrossing method, various types of Direct Extreme Value Analysis, Peterka's method and a Peak Distribution method. The Alternative Upcrossing method attracted the lowest Load Factors while the Largest Peak method required the highest.

The uncertainties due to the digitisation technique, which can randomly clip the peaks, and the non-stationarity of the signal are quite significant for pressure tests. The Coefficients of Variation due to the combined effects of the digitisation process and non-stationarity on peak pressures were significantly higher than those for the mean and standard deviation pressures. Uncertainties due to non-stationarity and the digitisation technique were much higher for the Largest Peak method than for the Upcrossing methods.

The effect of the various methods of analysis was minimised by choosing suitable probability levels for the empirical methods of analysis. However, it is important to note that some methods are more sensitive to the adjustment of the sampling parameters than others. For the same precision, the Peak Distribution method and Peterka's method require a sample length of 1 hour (prototype) compared with 30 minutes using the Upcrossing methods or the Peak

Distribution method (using the Poisson distribution). An Alternative DEVA developed by the authors required half the number of data values as Gumbel's DEVA. The effects of the various linear unbiased estimators was found to be negligible.

Pressure measurement systems with a frequency response lower than 100 Hz generally cause excessive attenuation of peaks resulting in unacceptable results. It was found that the higher the sampling frequency the lesser the effect of the filtering frequency, provided that the filtering frequency is not less than 100 Hz. Also, as the filtering frequency is increased, the sampling frequency becomes more critical. This effect was found using our pressure measurement system and may differ for pressure measurement systems which have different frequency response characteristics, particularly for systems which have significant resonant peaks at the higher frequencies.

Acknowledgments

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