TOWARD THE IMPLEMENTATION OF ON-LINE STRUCTURAL MONITORING USING RTK-GPS AND ANALYSIS OF RESULTS USING THE WAVELET TRANSFORM

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Abstract

The aim of this paper is twofold. First, it describes a pilot project in Singapore, in which an RTK-GPS system has been installed for the purpose of monitoring the behaviour of a high rise building. This system will contribute to a project of monitoring that commenced in 1995 with the installation of two pairs of accelerometers and two UVW anemometers. The aim of this project is to capture the building loading and dynamic response during strong winds and remote earthquakes to aid local design code development. The GPS monitoring system installed on the Republic Plaza building (at 280m, the maximum height of any Singaporean building) generates on-line antenna coordinate measurements. These will complement and corroborate the acceleration data to provide the complete picture of the building displacement across the full spectrum of loading frequencies, allowing for direct estimation of lateral loads. The system design and installation is described. The second objective of this paper is to describe a wavelet analysis procedure that has been proposed for the extraction of both the high and low frequencies of the structural dynamics from the 'raw' RTK-GPS results. The results of tests of this time series analysis procedure will be presented.

1. Introduction

Today, there are many more large and/or tall engineering structures than in the past. These structures are being designed to be much more flexible, and to resist extensive damage from changes in temperature, severe wind gusts and earthquakes. Structural engineers require precise, reliable instruments to resolve their concerns about angular movements, displacements and structural vibrations. Such instrumentation, and associated analysis tools, also aid in the development of building design codes.

For many years, monitoring the dynamic behaviour of engineering structures has relied on measurements made by instruments such as accelerometers and anemometers, installed on the structure of interest. The response data provided by such instruments normally require an integration process to arrive at the relative displacements. In contrast, the Global Positioning System (GPS) technology can measure directly the position coordinates, and nowadays relative displacements can be measured at rates of 10Hz and higher. This provides a great opportunity to monitor, in real-time, the displacement or deflection behaviour of engineering structures under different loading conditions, through automated 'change detection' and alarm notification procedures.

Recent studies have demonstrated the feasibility of deploying GPS instruments as 'smart sensors' for the dynamic monitoring of structures. Reports of experiments, and projects, related to such studies can be found in, for example, Ashkenazi *et al* (1997); Guo & Ge (1997); Cooper (1998); Brown *et al* (1999); Celebi *et al* (1998); Roberts *et al* (1999, 2000); and Duth & Hyzak (1997).

In this paper, the authors describe a project in which a high precision dynamic RTK-GPS system has been installed to complement existing structural monitoring instrumentation at the Republic Plaza Building, Singapore (Figure 1). The purpose of the GPS system is to provide, to a sub-centimetre accuracy, and at a rate of up to 10 samples per second, position vectors with respect to a fixed base station, of two antennas installed on the building parapet. The system will be operated in parallel with, and linked to, an existing logging system that records signals from accelerometers and anemometers. The system is intended to be 'open' to future software-based improvements in positional accuracy determination.

2. The System Design and Installation

The aim of the GPS-based measurement system is to determine, by direct measurements, the absolute structural deflections arising from ambient effects (such as temperature differentials, and static and dynamic components of wind). This system will allow the users to analyse data downloaded automatically from the site, and to occasionally adjust, by remote control, the system parameters. The existing monitoring instrumentation (Figure 2) has been upgraded to incorporate the new GPS component, as shown in Figure 3. The GPS component is composed of three main subsystems:

i) One base station comprising a dual-frequency, geodetic-grade GPS receiver installed at a nearby location (Finger Pier PSA Building), complete with mounting brackets, accessories and battery back up for operation for up to one day without power.

ii) Two 'rover' stations comprising a pair of dual-frequency GPS receivers installed on existing masts attached to the 66th level parapet of the Republic Plaza Building.

iii) Control centre PC running the Real-Time Monitoring software.

The communication link between the control centre PC and the GPS stations is provided via a UHF radio link to the base station and RS-232 connections to the 'rover' receivers. The UHF radio link transmits the base station GPS data to the rover receivers continuously. Instantaneous time and position results of the rovers' antennas can then be output via the RS-232 serial cables.

The system is designed to provide accurate position information of up to 10 samples/second in order to detect translational and torsional responses of the building to load. It will run in parallel (and synchronously) with the existing system of two roof-mounted UVW anemometers and B1 accelerometers. The two UVW anemometers supply six analogue signals, while the accelerometers supply four analogue signals, to a data logger installed in level 65 via multi-core cables. The existing system generates samples at 7.5Hz into consecutive records of 4096 samples, and stores the records to disk on event trigger.

A robust data logging system to capture data from the GPS system, as well as signals from the other sensors (temperature sensor, UVW anemometers and accelerometers), and to compute, for user defined periods, statistics for each of the measuring components has been designed. New data overwrites old data over a specified age with the option of storing data on event trigger conditions (for example, earthquake, strong wind, etc.), and all data stored on the logging system are retrievable by modem without interrupting the normal system operation.

Figure 1. Republic Plaza Building, one of the tallest buildings in Singapore.

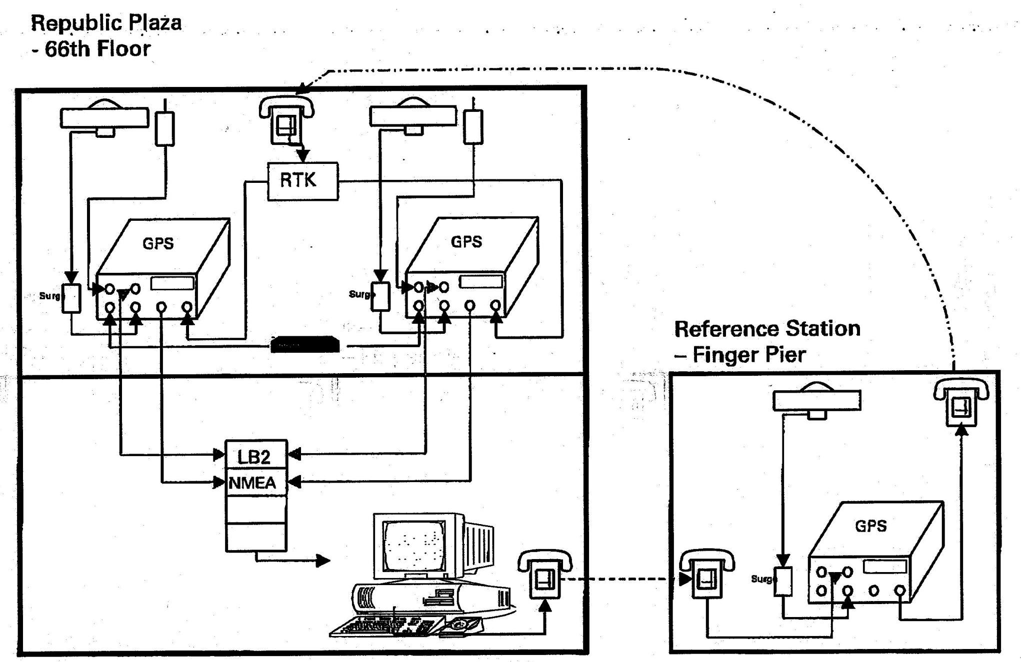

Figure 2. Layout of the GPS monitoring system: one base station at the Finger Pier (PSA Building), two 'rover' stations on the Republic Plaza Building.

Figure 3. Existing instrumentation on the Republic Plaza Building: a) View of level 66 roof/parapet; b) Sonic anemometer at East corner; c) Sonic anemometer at West corner; d) Typical antenna bracket at East corner; e) Close up of West corner; and f) Example of a GPS antenna (with earlier version of anemometer).

3. Structural Monitoring

Structural monitoring serves several purposes. For example, it can provide structural response data allowing for the as-built performance to be checked against design criteria, which will be an increasingly useful exercise given the move towards 'performance based design' of structures. Over a long period monitoring can also provide the opportunity to identify 'anomalies' or 'novelties' that may signal unusual loading conditions or modified structural behaviour, which can in the extreme case include damage of failure. A final use is to provide data for calibrating design codes. For the first application, the performance of the building has already been checked against the design and a complete understanding of the way the structure behaves has been obtained (Brownjohn *et al*, 2000; Brownjohn & Pan, 2001). For the second case, procedures are being developed to detect anomalies, but in this case a major value is for the calibration of local design codes.

Singapore has no seismic loading provision other than a provision for eccentric loading, which is regarded as being adequate to cover ground motions leading to 'base shear' of up to 1.5% of structural weight. When assessing the need to review this provision, signals of ground motion and building response due to 'long-distance' earthquakes are studied. In the case of Republic Plaza Building, signals from dozens of major and minor regional tremors have been collected since 1995 and are used with data from other sites, and some modelling of tremor attenuation affects and earthquake recurrence/magnitude relations, to arrive at a rational design basis (Pan, 1999).

Wind loading has usually been considered as the major form of lateral loading on a structure, and comprises static and dynamic components due to the mean value and turbulence of the wind, respectively. Singapore still uses the British design code, with design wind speeds from 29m/sec to 35m/sec accepted by local building authorities with no rational basis other than precedence. Singapore is almost unique in having a wind climate where the strongest effects are due to short-lived storm winds with low mean speeds and high turbulence, and a Singapore wind code is being developed. With the aim of ultimately providing for this, data on the wind and the relative amounts of static and dynamic deflection during storms and other strong winds will be invaluable for calibrating such a code.

Finally, thermal loading is frequently the cause of the largest deflections observed in structures. While the effect is of greatest concern in bridges, the effect on buildings can also be considered. The relative contributions of these various forms of loading can only be observed by a long term monitoring exercise such as has been carried out on bridges (Brownjohn *et al*, 1994), and in the case of Republic Plaza Building the challenges in terms of accuracy and resolution are more acute than for a flexible long span suspension bridge.

4. Experiment and Analyses of Results

A test experiment has been carried out to validate the concept of structural monitoring using GPS as outlined in the previous sections. The test was carried out on 24 January 2001, on the rooftop of the Geography and Surveying (GAS) Building at The University of New South Wales (UNSW). A baseline of approximately 10m was established and the observations were made over a period of 1 hour 50 minutes.

The set up included two Leica CRS1000 GPS receivers, a signal generator and a mechanical shaker. The base station antenna was set up on one of the astronomical pillar while the rover antenna sat on top of the mechanical shaker. Corrections generated at the base station were communicated to the rover station through an RS232 cable connection, and RTK position results were recorded at 10Hz. The signal generator supplied the mechanical shaker with random sine waves of both 'low' and 'high' frequencies within the range of 0.1Hz to 10Hz, simulating the response of dynamic structures under varying loading conditions. The 'low' frequencies were selected according to the typical values obtained during some past practical field experiments relating to structural monitoring by GPS. Lovse *et al* (1995), for example, measured a vibration frequency of 0.3Hz in both north-south and east-west directions for the Calgary Tower in Canada. Guo & Ge (1997) measured 0.174Hz and 0.205Hz in the east-west and north-south directions respectively, in the case of the Diwang Tower in Shenzhen City in southern China. Similar reports can be found in Celebi *et al* (1998) and Roberts *et al* (1999, 2000). The 'high' frequency values simulate the possible scenario of fast changing vibrations during the onset of some extreme loading event such as a typhoon or earthquake.

A method of analysis using 'Time-Frequency' wavelets has been applied to the fast GPS-RTK results from the experiment to automatically detect 'low' and 'high' frequency components embedded in the noisy time series, frequency changes and their onset times. The algorithm is formulated through the estimation of 'instantaneous frequencies' using the wavelet transform, and 'change detection' using the cumulative sum (CUSUM) scheme (Mertikas & Rizos, 1997; Mertikas, 1998/2000).

The wavelet transform of observations $X(t)$ is defined by the well known formula (Wickerhauser, 1994; Daubechies, 1990):

$$WD_x(\tau,a) = \frac{1}{\sqrt{|a|}} \int x(t).g^{*}\left(\frac{t-\tau}{a}\right)dt \qquad (1)$$

where $g(t)$ is the analysing wavelet, and a represent the temporal and scale parameters. This transform provides a localised analysis of the signal $x(t)$ around the point $(t,f_0/a)$ in the time frequency plane (f_0 being the central frequency of $g(t)$). While Fourier analysis only gives the frequency composition of a signal with the assumption that all the component frequencies are present from the origin to the end of the 'infinite' signal, the wavelet transform gives the time location of each frequency. This allows for the visualisation of transient frequencies and the determination of the occurrence of discontinuities in the signal. The algorithm which makes use of this property to detect frequencies present in the RTK data is outlined in the Appendix.

Figures 4, 5, 6, 7 and 8 show the test results, for which only the height component has been analysed (the antenna movement was excited in the vertical direction). In each of the figure a section of the noisy GPS-RTK time series containing the change point is plotted in (a). One can see that the results are very noisy due to the random observational noises -- thus any information about frequency is not obvious to the unaided eye. The plots in (b) are the results of the Fourier analysis, which only reveals the occurrence of different frequencies in (a), but doesn't indicate when the particular components occur within the signal. The plots in (c) show the instantaneous frequencies obtained through the wavelet transform using a time and frequency resolution of 60 samples and 256 points respectively. They indicate that a change has occurred in the frequency at some point. This change could be detected using a number of techniques such as CUSUM or GLR. In this case the CUSUM algorithm was applied (see Appendix). Plots in (d) show the change indicator given by testing the CUSUM value against a threshold using the hypothesis 'the mean of frequency has changed'. The probabilities of false alarms, missed detection and the mean time before detection depends on the value of the test threshold.

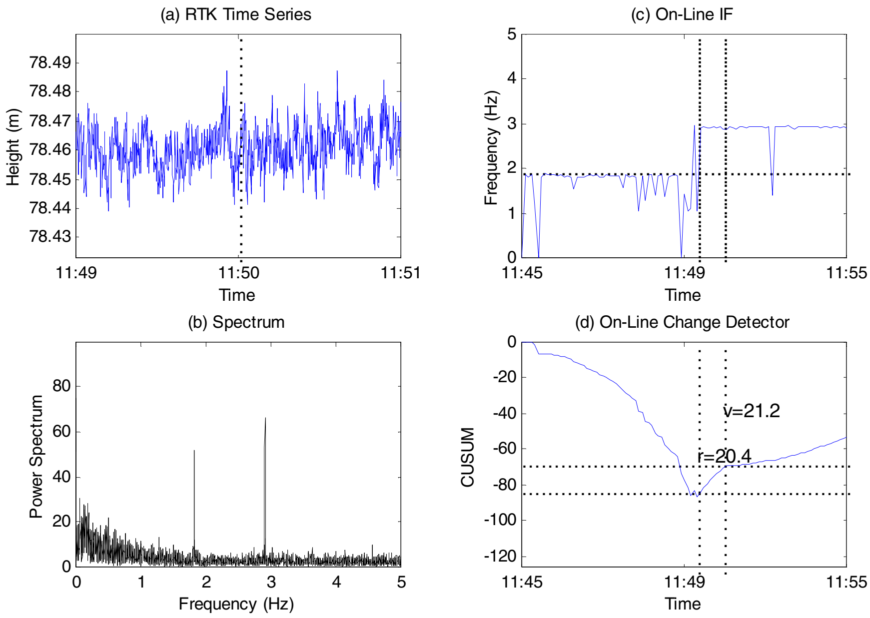

Figure 4. **High-to-high frequency change (2.0Hz to 3.0Hz at 11:50)**. CUSUM test parameters: initial mean μ_0 = 2.0Hz; anticipated shift Δ = 0.5Hz; threshold h = 16. Change detected at **11:51.**

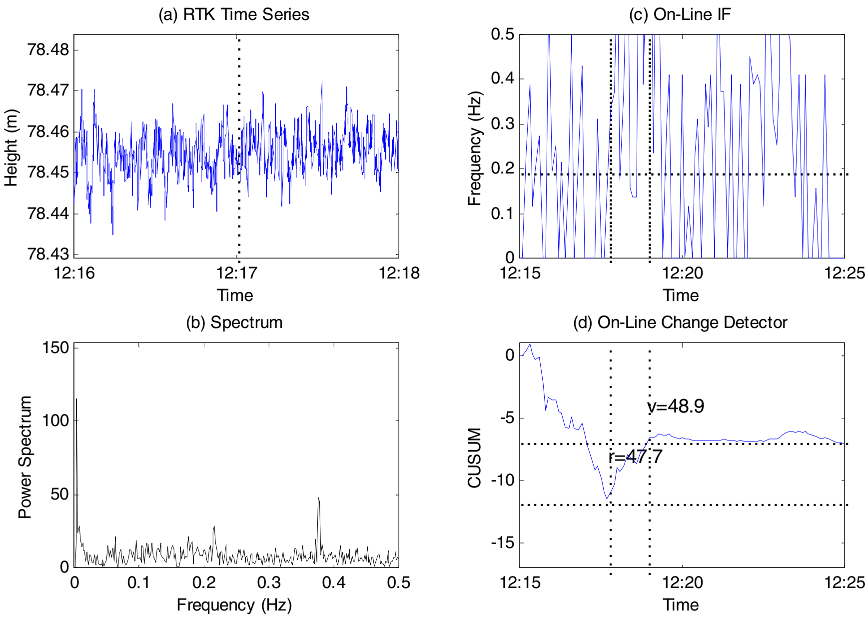

Figure 5. Low-to-low frequency change (0.2Hz to 0.3Hz at 12:20). Test parameters: initial mean μ_0 = 0.2Hz;anticipated shift Δ = 0.1Hz; threshold h = 4. Change detected at **12:17.**

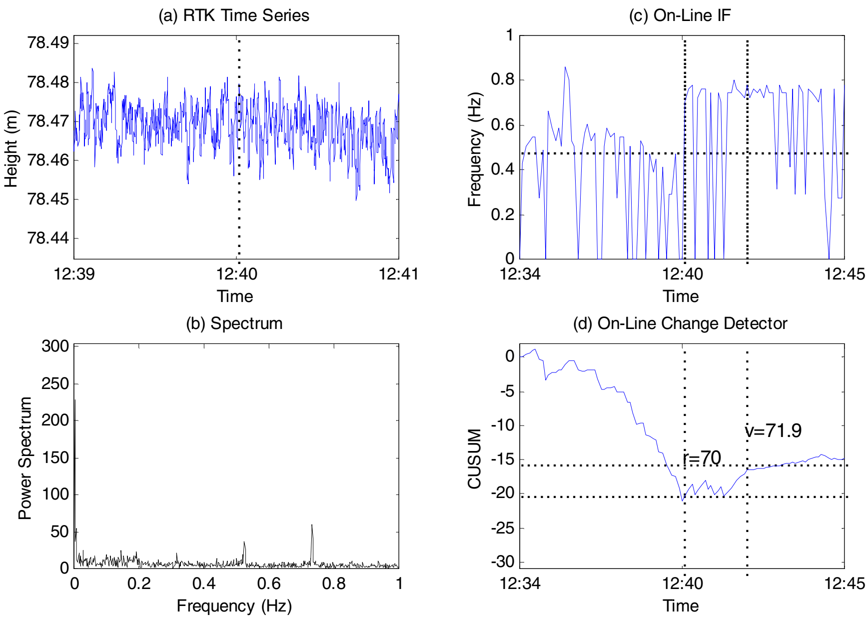

Figure 6. **Low-to-low frequency change (0.5Hz to 0.7Hz at 12:40)**. Test parameters: initial mean μ_0 = 0.5Hz;anticipated shift Δ = 0.1Hz; threshold h = 4. Change detected at **12:41.**

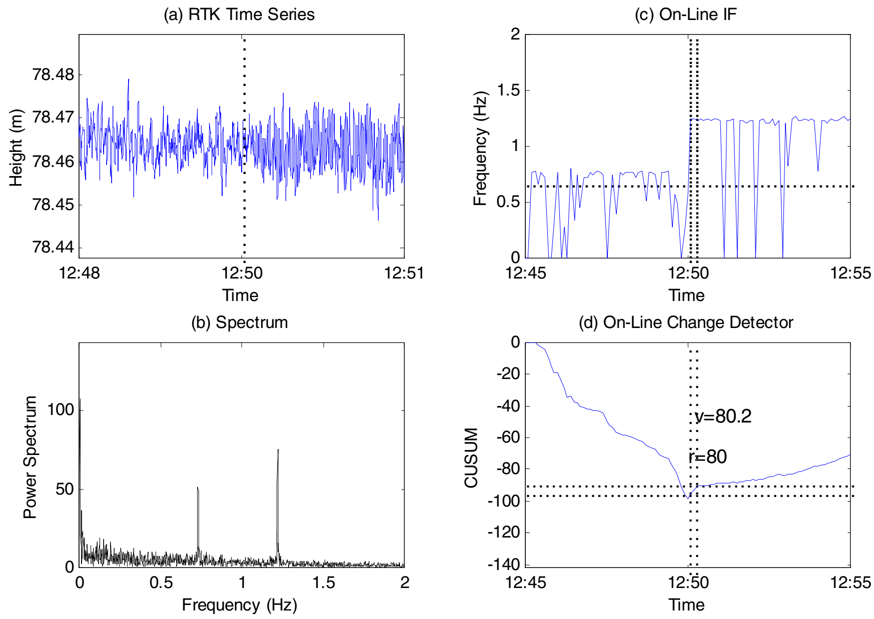

Figure 7. Low-to-high frequency change (0.7Hz to 1.2Hz at 12:50). Test parameters: initial mean μ_0 = 0.7Hz;anticipated shift Δ = 0.45Hz;threshold h = 4. Change detected at **12:50.**

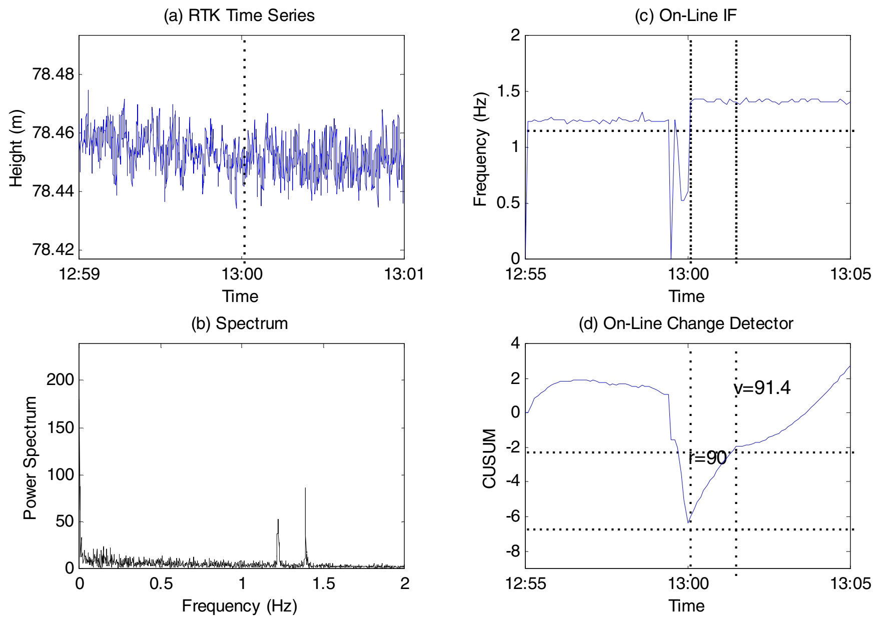

Figure 8. High-to-high frequency change (1.2Hz to 1.4Hz at 13:00). Test parameters: initial mean μ_0 = 1.2Hz;anticipated shift Δ = 0.1Hz; threshold h = 4. Change detected at **13:01.**

5. Concluding Remarks

A GPS-RTK deformation monitoring system has been installed on Singapore's tallest building, the Republic Plaza Building. This system complements sensors already functioning since 1995. This system of structural monitoring will serve several purposes. One objective of long term monitoring will be to identify 'anomalies' that may signal unusual loading conditions or modified structural behaviour. In the context of Singapore these conditions could be induced by strong winds or distant earthquakes. A secondary objective is to calibrate local building design codes.

The continuous time series of RTK solutions will be analysed to identify any changes in patterns of movement of the building. For this 'change detection' function an analysis technique based on wavelets has been developed and is currently undergoing testing. It is expected that by mid-2001 the analysis technique will be incorporated within the deformation monitoring system so that it operates automatically, in real-time, and only alerting an operator when a 'change' in the RTK time series is detected.

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Appendix: The Frequency Analysis Procedure

From equation (1) form a local estimation of the instantaneous frequency according to:

$$\omega(t) = \arg\left[\max_{\omega \in Q_\omega} \ \mathrm{WD}(t, \omega / a)\right] \tag{2}$$

with Q = { : 0 | | / (2T)} being the basic interval along the frequency axis, t is the time instant and T is the sampling interval. The time-frequency wavelet distribution is denoted by $WD(t,\omega /a)$.

Assume that at the time $t = n$ ($\leq N$), we have a record of new instantaneous frequencies:

$$\{\omega(t) : t = 1, \ldots, n\} \tag{3}$$

Compute for $r \leq n$

$$\begin{aligned} \lambda(t) &\approx \frac{\Delta}{\sigma_\omega^{\ 2}} \left[\omega(t) - \omega_0 - \frac{\Delta}{2}\right] \\ Z_r^n &= \sum_{t=r}^{n} \lambda(t) \end{aligned} \tag{4}$$

$$\Delta = \omega_1 - \omega_0 \,; \quad \omega_j = \mathrm{E}_j\{\omega_r^n\}\,; \quad j = 0,1$$

The decision rule with a chosen threshold h is:

$$\begin{aligned} &H_o \ \text{ if } Z_r^n - \min_{r \in M} \lambda(t) < h, \quad \text{for } t = r, \ldots, n \\ &H_1 \ \text{ if } Z_r^n - \min_{r \in M} \lambda(t) \geq h \quad \text{for } t = r, \ldots, n \end{aligned} \tag{5}$$

When a change is detected (H_1 has been decided), the detection time is:

$$\tau = \min\left\{ n : \arg\left[\min_{r \in M} Z_r^n\right]\right\} \tag{6}$$

and the estimated change time is given by:

$$\hat{r} = \min\left\{ \tau : \arg\left[\min_{r \in M} Z_r^\tau\right]\right\} \tag{7}$$

M is the set of time instants within which a possible change is searched up to time n. It is desired that the choice of M does not have a negative influence on the delay for detection and the false alarm rate.