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基於數位影像識別技術之結構健康監測系統之研究
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中文摘要

傳統結構量測系統為接觸式之有線儀器設備，必須將儀器設備安裝於結構系統上，再將各量測線材連接至數據擷取設備，並於安裝後試驗前進行各項檢測，需要大量的設備成本與建置時間，而數位影像技術屬於非接觸式之量測技術，不需從結構試體上安裝相關設備並佈置線材及連接設備，正逐漸被採用並進行相關研究。大多數的數位影像技術相關研究採用一般之數位相機，雖然簡單方便，但普通數位相機或數位攝影機之動態錄影功能，由於對普通使用者而言，其採樣頻率並不需要嚴格要求為固定，因此其影像之間隔時間並無法達到較為準確之要求。故本研究採用價格較昂貴的高速相機，以使影像之間隔時間能依據需求來設定，而獲得更準確的影像間隔時間。數位影像處理及分析一般應用在二維影像，藉由電腦之高速計算，分析影格之間的變化，進而求得試驗結構之影像位移。數位影像相關法計算影格區塊之間相關係數，以分析影格中試體相對位移像素，再搭配次像素分析可進而求得次像素位移，以增加量測精度。本研究發展之數位影像量測系統，硬體配備上包括高速數位相機、相機鏡頭、影像擷取卡、工業級電腦，軟體部份則包括高速數位相機搭配之設定軟體、LabVIEW 8.5 以及 MATLAB 2007a，再搭配相關電腦程式，包括：動態影像擷取程式、灰階影像轉存程式、影像強化程式、結構位移分析程式、邊緣偵測程式、頻率分析程式等。本研究除了發展數位影像量測系統，也在本校結構大樓之小型震動臺及大型震動臺分別做了多次實驗，甚至亦前往國家地震中心進行結構地震模擬實驗，除了獲得許多地震中心提供的寶貴實驗資料，本系統亦同時獲得所需的影像資料，分析結果與地震中心之 LVDT 位移資料相當符合，也代表著本系統之確實可行。

關鍵字:數位影像相關法、次像素分析、頻率響應函數、結構健康監測

英文摘要

Conventional structural measurement system is based on contacted cable equipments installed on the structural system and many tests must be completed before experiment. Moreover, a large amount cost and build time were required for setting the traditional measurement system. In contrast, the digital imaging technology is non-contact scheme for measurement system and has been applied in diverse domains based on common purpose digital cameras. However, the shutter time for general digital cameras is not very accurate; hence, they can not reach the research needs. Herein, a high-speed digital camera which can set the exact shutter time is employed as measure requirements. In term of hardware, the proposed digital image measurement system includes high-speed digital camera, zoom lens, image capture card, and industrial computer. In term of software, application programs are developed based on LabVIEW 8.05 and MATLAB 2007a API. The scheme of digital image processing (DIP) can be utilized to rapidly calculate and analyze changes of corresponding pixels among frames and resolved the displacements of the measured structure. Also, the digital image correlation method is utilized to analyze the correlation coefficient of image blocks to estimate the displacement of structure. To improve the measurement accuracy, the approach of sub-pixel analysis is adopted for the integer displacement time history. Finally, the feasibility and robustness of the proposed digital image measurement system were assessed using a 1/8-scale three-storey steel-frame model in NCREE. Meanwhile, an FRF-based damage detection approach was also employed to locate the damage location of the frame with different damage scenarios. The experiment results reveal that the proposed digital image measurement system is feasible and reliable non-contacted structural measurement system.

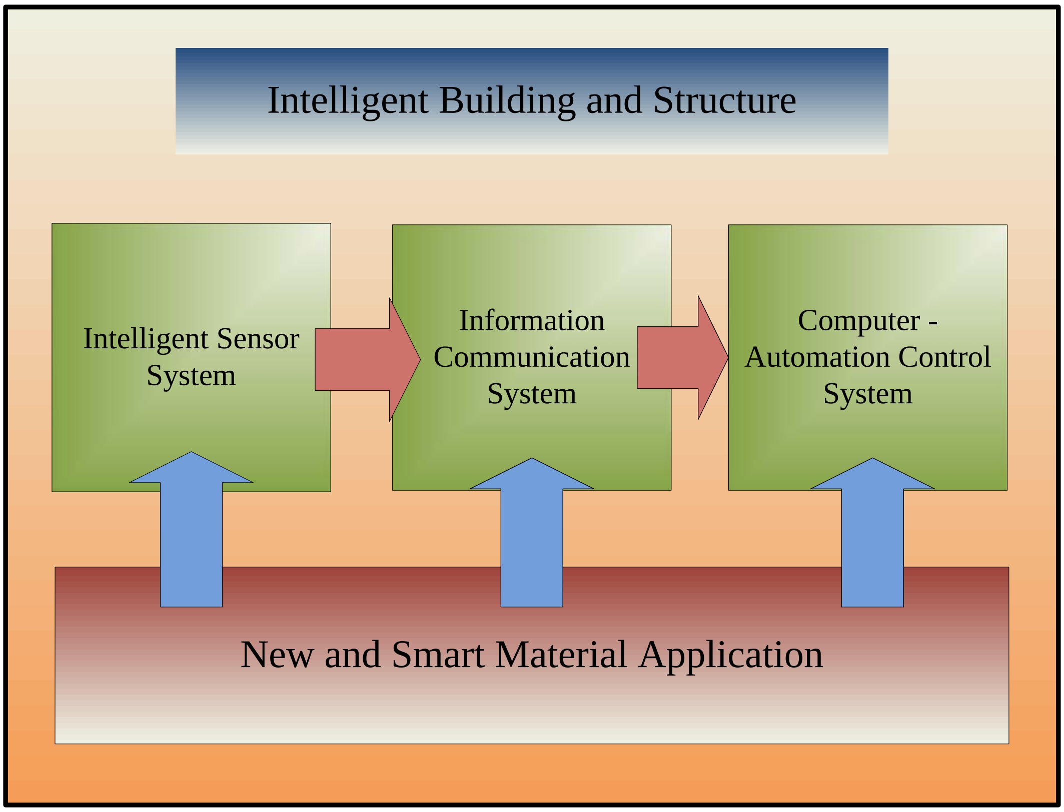
Keywords: digital image correlation method, sub-pixel analysis, frequency response function (FRF), structural health monitoring (SHM)

目錄

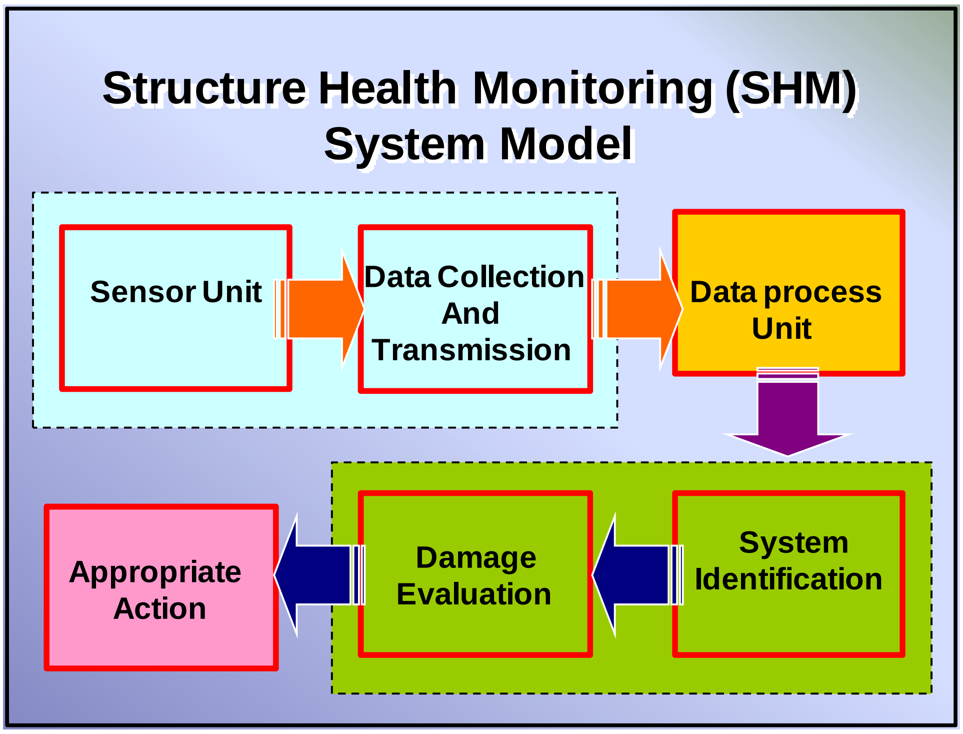
一　前言

現今的土木公共基礎建設，已遠比過去具有高度更高、跨度更大、斷面更小的特性，而且材料之選用與使用，更是經濟節省，同時達到造型美觀上的要求；此時，監測系統之有效性與靈敏性，將更加關係土木結構物之使用功能與服務品質。結構健康監測隨著日益增加的地震、水災、風災、土石流等天然災害，也愈來愈突顯出其重要性。當自然災害造成結構或生命財產的損失，才來進行後續的彌補或撫卹，是絕對無法被萬千民眾接受，因此相關的結構監測系統，甚至是預警系統的需求，就是國內外學者所需致力研究之課題，以及未來各領域之一致趨勢。

智慧建築與結構利用新型智慧材料，將其逐步應用在智慧感測系統（包含智慧結構健康監測系統、智慧溫度空調控制系統、火災偵測系統等）、資訊通訊系統、電腦自動化控制系統，可由圖一表示。結構健康監測系統屬於智慧感測系統之一部份，同樣亦是運用新型而智慧之相關感測元件，來建構出一套適用之智慧監測系統。



圖一　智慧建築與結構的元素



圖二 結構健康監測系統架構圖

智慧型結構健康監測系統一般由感測器單元、資料擷取與傳輸單元、資料處理單元、系統識別與損壞評估單元所組成如圖二所示，主要用來評估結構物的健全度並監控與維護結構物。結構監測系統主要利用透過長時間應力和勁度的衰減等來對結構物做出監測或是判斷突發的事件對結構造成之損害程度。Kiremidjian 等學者(Kiremidjian et al.)並將結構監測系統分為兩大類：(1)在結構上選擇某點量測其特徵值，比如說量測結構物的應變，再根據其值對結構物的長期健康狀態做相關比對；(2)利用不同的參數以系統識別的方法判定結構物的損害程度。智慧結構健康監測系統的最重要的就是前端的感測器，因為若是一開始所獲得的資料不正確或是不能有效的感測到資訊，那對於後端系統識別與損壞評估而言就失去意義，因此感測器對於結構監測系統來說是相當重要的一個因素。傳統的感測器主要為將受測物體所擷取到的資訊轉換成電子訊號，此類感測器可以拆解為 3 個主要的部份(Ruiz-Sandoval 2004)：(1)感測元件(例如加速度計)；(2)訊號狀態和處理(例如訊號放大、線性化、補償、過濾等)；(3)感測介面(例如用電線將其與其他電子裝置做連結)。而本研究主要將傳統感測器，改由高速數位相機來取代，透過影像擷取卡將所擷取的影像儲存於電腦中，再經過電腦程式分析數位影像，進而估算出結構物受力後之變形。而影像處理技術則可以較低成本進行受測物體的變形量測，在日益精進的光學技術研發下，數位影像解析度

愈來愈高，使得量測精確度相對提高，因此採用數位影像處理技術已成為土木工程中日趨成熟之應用。對於數位影像靜態的變形量測而言，只要二張變形前後的數位影像，藉由數位影像處理分析，即可求得影像中特定位置之變形量。若要量測結構物的歷時變化，則可由數位影片或連續影像中，逐步計算分析每二張數位影像之變化，進而繪出結構物之位移變化歷時曲線。

二 研究目的

現今，智慧感測技術與資訊科技的進展使得結構智慧化監測變成可能，多數的結構已建置有許多的先進的加速度計、速度計、光纖感測器等等的感測儀器。然而，在有限經費的考量上，不可能在大範圍佈置大量的感測節點，且某些構件位置布設感測器也相當的不易，而無線感測網路與數位影像的應用恰可補強這一部分的機能。因此，本研究將進一步對影像處理技術於土木結構健康監測進行一系列之研究，發展數位影像識別技術之結構健康監測系統，此系統將可以有效提高土木公共基礎建設之防災監測的能力。

傳統實驗量測系統需要大量的建置成本與建置時間，而採用數位影像技術之量測系統有著省時快速、方便、非接觸式等優點，且光學技術日新月異，對於影像資料的解析度愈見強大，得以更進一步提升效率及效能。只是對於動態影像錄影之快門，無法精確設定，而本研究採用之高速數位相機，可自定所需之快門時間，以決定精確的影像取樣率。因此本研究之目的將發展一個數位影像實驗量測系統，作為實驗量測位移之替代選擇，系統架構如圖二所示。此系統運用高速數位相機搭配光學鏡頭，影像訊號由影像擷取卡抓取至工業級電腦，經過電腦程式分析處理以獲得推估之位移歷時資料，若再配合其它分析軟體則可進行結構健康狀態判別。因此，一個與傳統監測系統不同的數位影像結構健康監測系統即可逐漸成形，不僅建置成本可以降低，同時建置時間也可大幅縮短，並能達到足夠的資料精確度，以提供實際需要之應用。

三 文獻探討

目前國內外已有許多數位影像技術應用於各種不同領域之相關研究，除了應用在土木工程結構，也包括天文監測、醫療檢測、產品品質控制及天氣預測等方面。同時由於奈米科技的進步使得數位影像解析度愈來愈高，量測資料精確度得以更加提高。

Masanobu Shinozuka 等人(2000)針對數位影像處理技術應用於系統識別上，進行概念性驗證(Proof-of-concept)之實驗，顯示出數位影像處理技術得以發展出有效的演算法進行系統識別。Gongkang Fu 和 Adil G. Moosa (2001)以高解析度影像進行結構損壞檢測。A. Mazen Wahbeh 等人(2003)運用影像技術建立一個經濟而又強健的量測系統，直接而同時量測不同位置之橋樑絕對位移歷時資料。Jong Jae Lee 和 Masanobu Shinozuka (2006)利用數位影像處理技術即時量測橋樑位移。M. Meo 等人(2006)利用 GPS 即時量測橋樑運動位移，以小波模態萃取技術(Wavelet Modal Extraction)分析橋樑之模態頻率及阻尼。Guobiao Yang 和 Kui Wu(2007)利用長焦距顯微數位相機取得樣本影像及目標影像，求解兩者影像區塊相關係數之最大值，據以獲得位移量測數值。C. C. Chang 和 Y. F. Ji(2007)提出基於近景數位攝影及電腦視覺原理之數位影像處理技術，利用二部數位攝影機量測二維或三維的振動響應，研究結果可獲得相當準確之位移量測，使用之參考目標類似於西洋棋盤的四格黑白方格。施明祥等人(2008)將數位影像相關法應用於橋樑動靜態變位之量測。

在結構監測應用方面的研究也相當的多(C. S. Fraser and B. Riedel,2000; G. Fu and A. G. Moosa,2001; G. De Schutter,2002; H. G. Sohn et al.,2005; H. G. Maas and U. Hampel,2006; Y. Ohnishi et al.,2006; T. Yamaguchi et al.,2008)，Fraser 與 Riedel(2000)應用數位影像技術於鋼梁溫度變化造成之變形量測，實驗環境從 1100 度的高溫回復到常溫。Fu 和 Moosa(2001)提出使用高解析影像檢測結構損害之方法，使用機率損害指標進行交叉診斷識別結構勁度損壞比率。Schutter(2002)使用顯微攝影機針對混凝土梁及版進行裂縫檢測試驗，並以一歷史建築物實地檢測，與傳統檢測技術比較，該種結合數位影像及自動影像分析之方法，可獲得很準確的結果。Hong-Gyoo Sohn 等人(2005)使用現成的數位相機為影像擷取設備，於監測期間取得一系列不同時間點的數位影像，為了解決相機拍攝過程中造成的座標偏移，該研究使用 modified iterated Hough transform (MIHT)演算法進行二維投影轉換，最後的結果亦成功偵測裂縫變化及準確地數據。Hans-Gerd Maas 與 Uwe Hampel(2006)提出以影像處理

技術應用在工程材料實驗及大型結構監測最主要的優勢在於，可以同時針對大量的檢測點進行高度自動化之量測。 Y. Ohnishi 等人(2006)提出以數位影像技術應用於邊坡監測，該研究使用 Moore-Penrose generalized matrix inverse，由相機、量測點及數位影像的幾何關係，在未設定任何控制點之下，求得量測點之間的距離。Tomoyuki Yamaguchi 等人(2008)提出以影像為基礎之混凝土表面裂縫檢測方法，其檢測方式依據影像的亮度及形狀執行類似液滲透現像之滲透處理程序，再執行雜訊處理，最後執行二元化得到純黑白之裂縫影像，由量化分析之結果顯示該研究優於以往之方法。

一般而言，使用數位影像分析之硬體設備，可採用普通數位相機、數位攝錄影機，通常都能擷取動、靜態數位影像，而在動態錄影方面，通常數位相機多以 30fps, 24fps 及 15fps，就普通使用者而言，並沒有高速攝影之需求。然而，若需要量測高頻之訊號，以進行更複雜的學術研究，則高速數位相機為一不可或缺之設備，同時其準確的快門時間設定，也提供研究者更精確的量測數據。

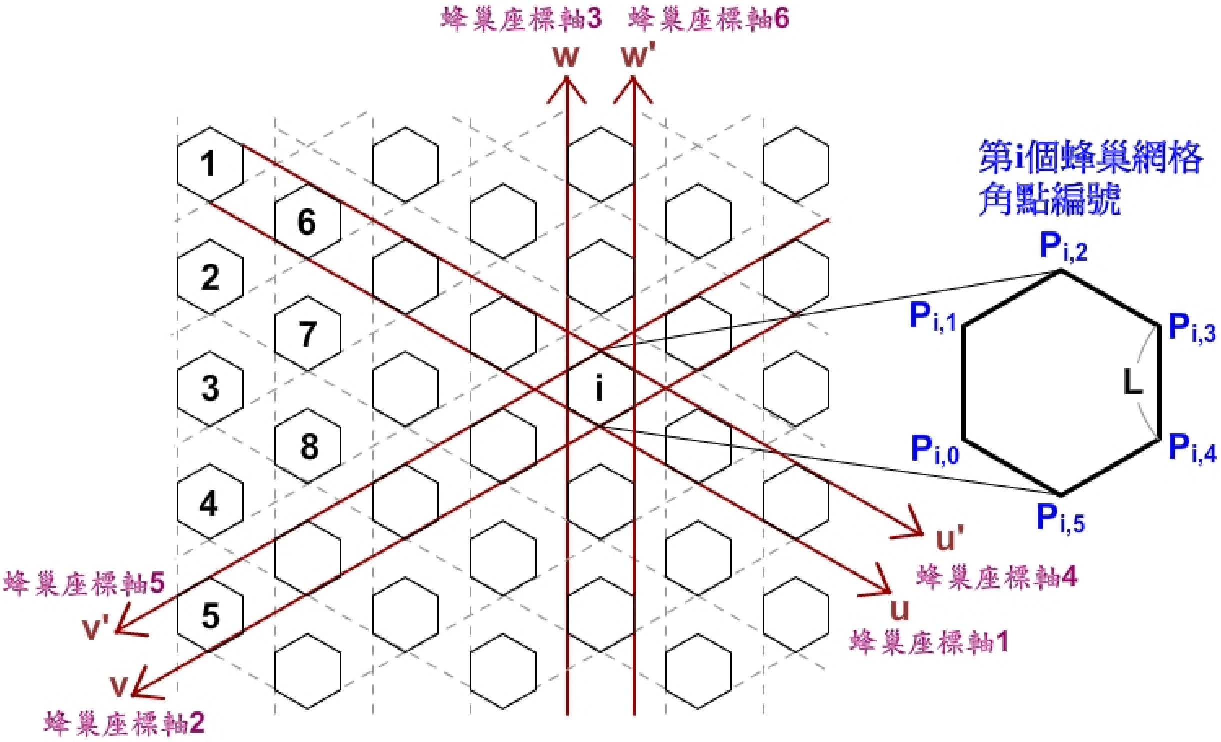
在數位影像次像素估算研究方面，M. D. Pritt(1994)提出一個可以達到次像素層級之遙測影像自動配準演算法。H. Shekarforoush 等人(1996)提出利用互功率頻譜，求出多相元件之和即可估算出影像次像素偏移量。Kenji TAKITA 等人(2003)提出基於相位相關之高準確次像素影像配準之演算法。Jun Zhang 等人(2003)提出一個高效率的以梯度為基礎之演算法，結合廣泛使用的數位散斑相關法改善次像素配準。Murat Balci 和 Hassan Foroosh(2006)提出在頻率域直接估算影像間次像素層級之偏移量。Li Fuwen 等人(2007)基於數位影像相關法結合灰階值內插方法，以推估影像之次像素位移。

四　研究方法

本研究將發展一個蜂巢網格量測法之數位影像技術，應用於結構健康監測上，將六角形蜂巢網格參考目標加諸於結構試體上，配合數位影像技術，擷取連續之數位影像進行分析計算，以估算結構動態系統參數，並據此評估結構整體之健康程度及提供預警功能。

數位影像處理技術從1960年代開始萌芽，由於早期電腦系統尚未普及化，其計算處理成本相對而言非常昂貴。到了1970年代開始，由於電腦硬體設備價格慢慢降低，使得數位影像處理技術漸漸發展開來。而到了2000年以後，愈來愈快的電腦設備及訊號處理器讓數位影像處理技術成為功能強大又非常便宜的處理工具。一般數位影像處理技術適用於影像分類、影像特徵擷取、影像樣式識別、多尺度訊號分析…等，且已被廣汎應用許許多多不同的學術領域。CCD影像感測器由貝爾實驗室於1960年代末期研發初來，原本只是當成電腦記憶元件使用，後來發現矽對於波長1.1微米以下的光具有高靈敏度，才轉為訊號處理和擷取影像之技術。另一種CMOS的影像感測器架構在1960年代也已經具備，只是一直到1993年美國太空總署噴射推進實驗室的一批研究人員才研發出可供應用之元件。影像與圖形辨識屬於資訊學門領域，而在數位光學技術日見成熟後，數位影像技術陸續被應用在其它各個不同的學術領域，例如：醫學、農業、航太、機械、化學、土木…等。

本研究提出之蜂巢網格（圖三）量測法，此種六角網格之參考目標點之檢測，可以使用影像處理技術中的邊線偵測找出各個網格的邊線，再由各邊線的交點決定其影像座標，分別以Pi,0至Pi,5表示。比較二張數位影像的角點座標位置，即可快速決定各角點之位移，分別以di,0至di,5表示，進而推估網格內各點位移及其應變。若分析高速擷取的連續數位影像，則可求得各點之位移變化歷時曲線，進一步執行結構系統參數識別。



圖三 蜂巢網格參考目標

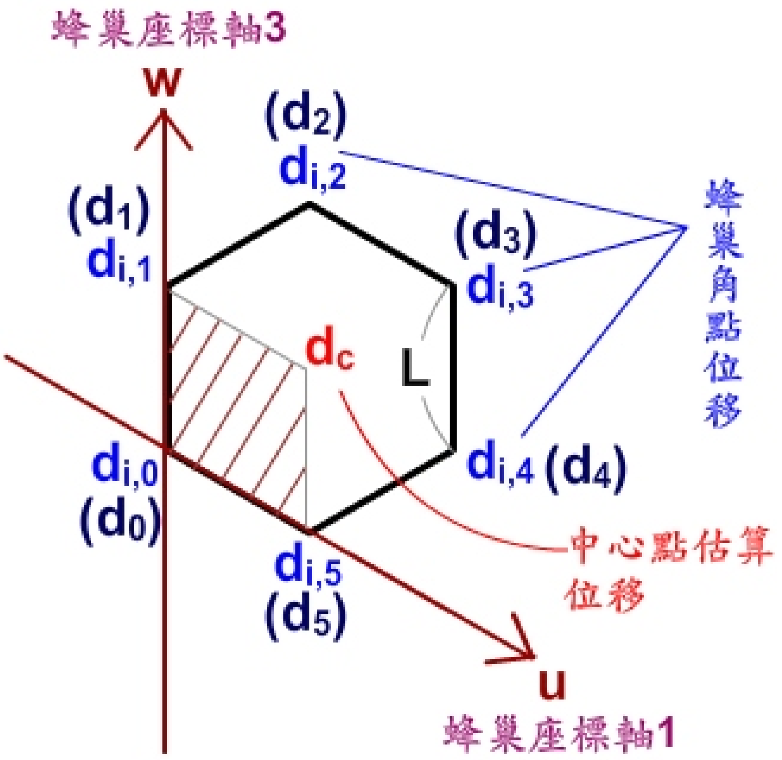
網格內部各點的位移數值估算簡述如下，若以蜂巢座標軸 u 及 w 為參考座標軸，並將座標軸的界限設為 0~L，亦即將其長度限制在蜂巢邊長範圍內，則該參考座標軸將包含三分之一個蜂巢網格平面，如圖四所示。另外三分之二則可分別由座標軸 v,w’以及 u’,v’予以包含，這三組參考座標軸包含的三個平面的共同交點恰為蜂巢網格之中心點。對於 uw 座標平面而言，其座標原點在 $P_{i,0}$ 的位置，將蜂巢角點位移調整如下：

$$
\begin{aligned}
d_0 &= d_{i,0} - d_{i,0} = 0 \\
d_1 &= d_{i,1} - d_{i,0} \\
d_2 &= d_{i,2} - d_{i,0} \\
d_3 &= d_{i,3} - d_{i,0} \\
d_4 &= d_{i,4} - d_{i,0} \\
d_5 &= d_{i,5} - d_{i,0}
\end{aligned}
$$

而蜂巢網格中心點的位移 d_c 則以下式估算之

$$
d_c = \frac{\sum_{i=0}^{5} d_i}{6}
$$

由 d_1,d_c,d_4 三點位移可繪製出二次拋物線，並推導出二次曲線方程式，再類推至 u 軸。同理，亦可由 d_2,d_c,d_5 三點位移可繪製出二次拋物線，並推導出二次曲線方程式，再類推至 w 軸。由 uw 所形成的參考平面及加上位移維度即形成三維空間，求得空間上的曲面，即為 uw 各點之估算位移。

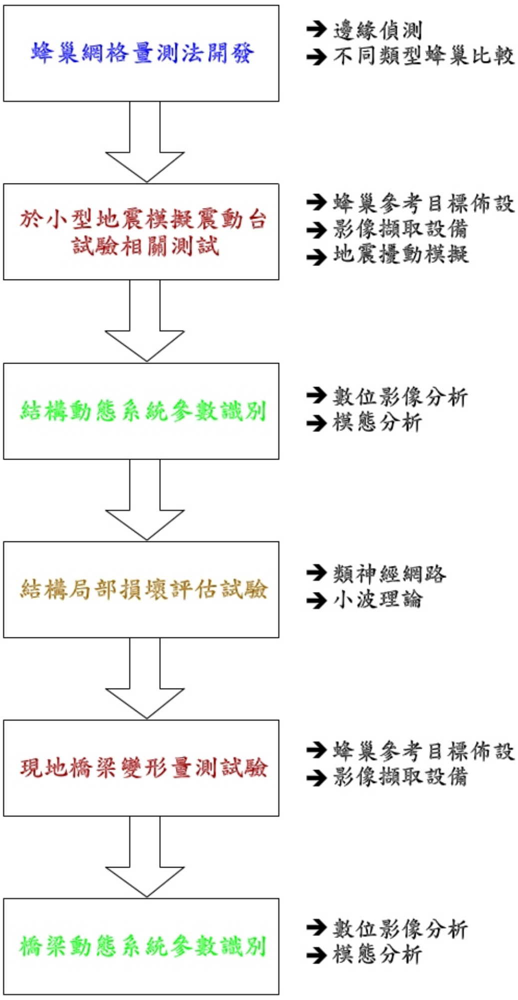


圖四 蜂巢座標軸與蜂巢關係圖，斜線部份表示座標軸涵蓋的平面

本研究為獲得更精細的影像變化，數位影像擷取設備使用影像擷取速率高達每秒 500 個影格之高速數位相機，如圖五，該機型為 Basler Vision Technologies 公司之 A504kc，傳輸介面採用傳輸速率將近 2.4Gbps 的 Camera Link，搭配美商國家儀器的影像擷取卡 NI PCIe-1429。由於需要傳輸大量的影像資料並進行資料存取作業，因此亦需搭配高速儲存設備，才能完全發揮其高速擷取之效能。由於高速的擷取速率，代表著相機曝光時間相對減少，因此實驗過程中若能增加其它額外輔助光源，將可使獲得之數位影像品質予以提升，進而提高資料分析準確度。

圖五 數位影像擷取設備

本研究主要利用蜂巢網格量測法於分析計算，以求得結構之準確位移，進而推估結構動態系統參數，結合類神經網路及小波轉換，以判別結構系統之損壞程度。本研究擬以三年的時間進行一系列數位影像技術於結構健康監測與遠端局部損壞檢測系統之相關研發工作，以及實驗室模型動力試驗等相關研究工作。本研究之分析流程圖可見圖六。



圖六 研究流程圖

數位影像處理技術應用於結構位移量測時，常用的參考目標有圓點、方格、散斑等方式，圓點參考目標只能決定單點位移，方格參考目標可決定四個角點位移，並進一步以線性推估方格內其它點之位移。以隨機散斑的量測方式，則以兩張變形前後的數位影像中的部份區塊內容進行相關係數計算或其它匹配演算法，找出其最大相關性以決定區塊之位移，理論上可以找出影像對中所有點的位移，只是花費的計算時間成本較高。蜂巢網格量測法則嘗試以六角網格為參考目標（如圖三），快速找出網格格點位移，再去推估網格內部各點之位移。

圖五參考目標之實線部份表示實際塗佈於結構試體，虛線部份代表每個蜂巢網格的參考座標軸。每個蜂巢網格以左下方為座標原點 p_0，順時針方向分別為 p_1~p_5，假設已求得各點 X 方向的位移 d_0~d_5，將各點位移減去 d_0，使 p_0 點之位移為零。將各角點位移取其平均當作網格中心點之估算位移 d_c，以該中心點位移加上通過中心點直線的另外二點位移(例如：d_1,d_4)，由以下三點位移函數值，即可求得直線 $\overline{p_1 p_4}$ 之位移二次曲線方程式 f(u)。

$$f(0)=d_1$$
$$f(L)=d_c$$
$$f(2L)=d_4$$

令 $f(u)=au^2+bu+c$

將上述三點代入方程式求解未知數 a,b,c，即可求得

$$f(u)=\frac{(d_1+d_4)-2d_c}{2L^2}u^2-\frac{(3d_1+d_4)-4d_c}{2L}u+d_1$$

同理，直線 $\overline{p_5 p_2}$ 之位移二次曲線方程式 f(w)如下

$$f(w)=\frac{(d_5+d_2)-2d_c}{2L^2}u^2-\frac{(3d_5+d_2)-4d_c}{2L}u+d_5$$

將 f(u)曲線方程式的曲率保留，重設一方程式如下

$$g(u)=\frac{(d_1+d_4)-2d_c}{2L^2}u^2+bu+c$$

u 軸的兩點位移函數值如下

$$f(0)=d_0$$
$$f(L)=d_5$$

將其代入方程式求解未知數 b,c，即可求得

$$g(u)=\frac{(d_1+d_4)-2d_c}{2L^2}u^2-\left[\frac{d_5-d_0}{L}-\frac{(d_1+d_4)-2d_c}{2L}\right]u+d_0$$

又因為先前已經將 d_0 位移調整為零，因此上式可簡化如下

$$g(u)=\frac{(d_1+d_4)-2d_c}{2L^2}u^2-\left[\frac{d_5}{L}-\frac{(d_1+d_4)-2d_c}{2L}\right]u$$

上式即為 u 軸各點之估算位移方程式，同理，w 軸之方程式則如下

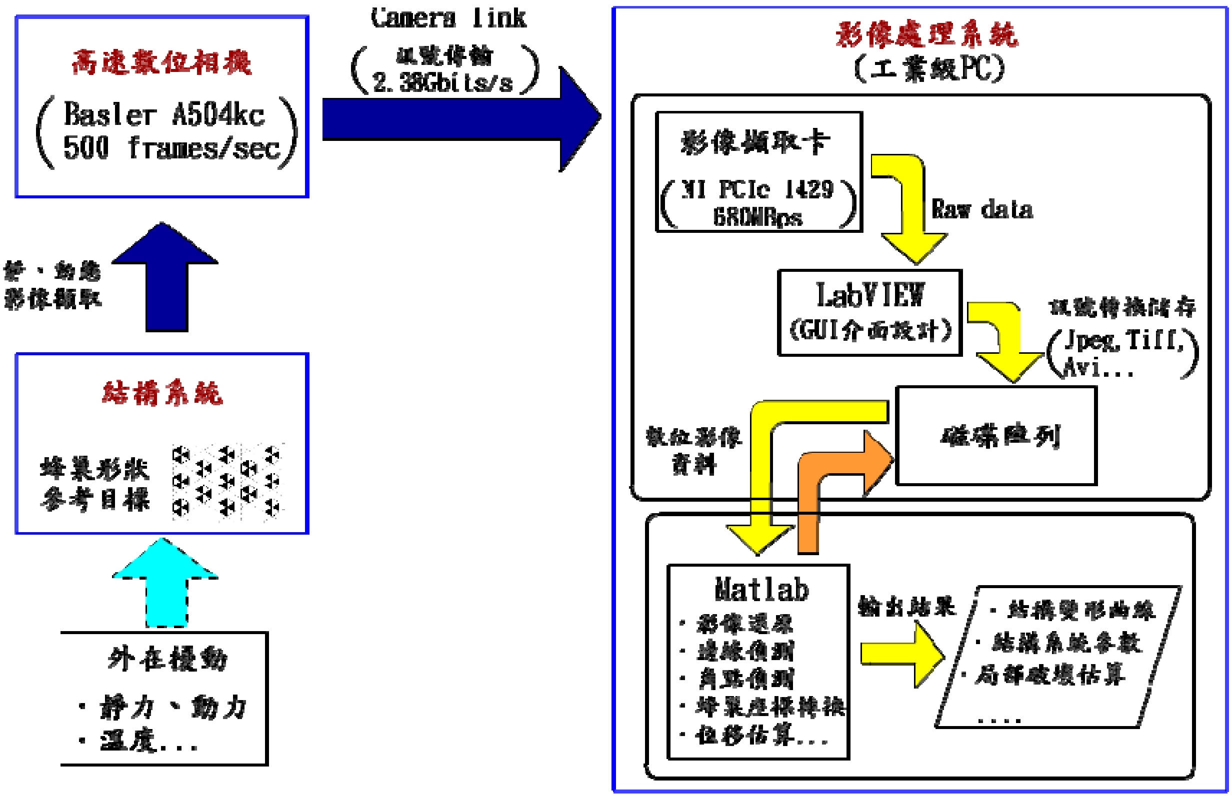
$$g(w)=\frac{(d_5+d_2)-2d_c}{2L^2}u^2-\left[\frac{d_1}{L}-\frac{(d_5+d_2)-2d_c}{2L}\right]u$$

利用 f(u),f(w),g(u),g(w)即可推算出 uw 座標軸涵蓋的三分之一個蜂巢網格的各點位移，其它各個蜂巢網格亦可使用此法估算其位移。至於每個蜂巢網格周圍空白處，由於蜂巢角點均勻分佈，故亦可取得正確適當的六個角點，估算出空白蜂巢網格之各點位移。因此，只要在處於蜂巢網格涵蓋之表面，皆能使用此法估算出表面位移。

五　研究結果與討論

5.1 數位影像量測系統架構

本研究主要硬體設備包括：結構試體、高速數位相機、影像擷取卡、工業級電腦，整體系統架構圖如下所示。首先於結構系統上佈設蜂巢網格標記做為參考目標，以地震模擬振動臺施加模擬地震力於結構試體上，產生結構變位，藉由高速數位相機擷取數位影像，透過訊號傳輸線至影像擷取卡，儲存於工業級電腦的高速儲存設備。影像資料蒐集完畢後，再利用 Matlab 及 LabVIEW 等電腦軟體進行分析，產生結構試體之位移變化歷時曲線，並利用快速傅立葉轉換及小波轉換，於頻率域中進行結構損壞分析。



圖七 數位影像處理技術於結構系統量測架構圖

5.2 數位影像漏失補償

本研究利用高速數位相機，由影像擷取卡將大量影像資料傳送至工業級電腦進行分析，然而由於資料量龐大導致資料儲存過程當中，有部份影格資料會發生遺漏之情況。經由程式記錄下所遺漏之影格編號，再於分析過程中，以內插法予以補償，不致於產生訊號偏移之狀況，以提高後續訊號分析之準確度。以 1/8 比例三層樓剛構架實驗的結果，若不管遺漏之影格，則所求得之頻率為 1.847654298 ，經過補償之後所求得之頻率則為

1.835517218 ，與 LVDT 所求得之頻率為 1.836330953 比較，發現確實可以提高識別的準確度。

5.3 結構損害評估方法

本研究採用研究團隊先期使用之頻率響應函數(Frequency Response Function, FRF)或是頻率響應函數曲率(Frequency Response Function Curvature, FRFC)，作為結構健康監測方法，此法又稱為實驗模態法，主要的優點是不需要進行費時的系統識別來求出結構的模態參數。

頻率響應函數與頻率響應函數曲率法：一個多自由度剪力屋架結構系統可以表示如式(1)所示：

$$[M]\{\ddot{x}(t)\}+[C]\{\dot{x}(t)\}+[K]\{x(t)\}=\{f(t)\} \tag{1}$$

其中$[M]$, $[C]$ 與 $[K]$ 分別為 $N\times N$ 質量、阻尼與勁度矩陣。$\{x(t)\}$與$\{f(t)\}$ 分別為 $N\times 1$ 的時變位移向量與外載重向量。$[M]$, $[C]$ 與 $[K]$ 可以表示成

$$[M]=\begin{bmatrix} m_1 & & \cdots & & 0 \\ & m_i & & & \\ \vdots & & \ddots & & \vdots \\ & & & m_{N-1} & \\ 0 & & \cdots & & m_N \end{bmatrix} \tag{2}$$

$$[C]=\begin{bmatrix} c_1+c_2 & -c_2 & & & & & \\ -c_2 & c_2+c_3 & -c_3 & \cdots & & 0 & \\ & -c_3 & c_3+c_4 & & & & \\ & \vdots & & \ddots & & \vdots & \\ & & & & c_{N-2}+c_{N-1} & -c_{N-1} & \\ & 0 & & \cdots & -c_{N-1} & c_{N-1}+c_N & -c_N \\ & & & & & -c_N & c_N \end{bmatrix} \tag{3}$$

$$[K]=\begin{bmatrix} k_1+k_2 & -k_2 & & & & & \\ -k_2 & k_2+k_3 & -k_3 & \cdots & & 0 & \\ & -k_3 & k_3+k_4 & & & & \\ & \vdots & & \ddots & & \vdots & \\ & & & & k_{N-2}+k_{N-1} & -k_{N-1} & \\ & 0 & & \cdots & -k_{N-1} & k_{N-1}+k_N & -k_N \\ & & & & & -k_N & k_N \end{bmatrix} \tag{4}$$

其中， m_i, c_i,與 k_i 分別為第 i 個自由度的質量、阻尼與勁度。

而外力與解可以表示成以下形式：

$$\{f(t)\}=\{\mathrm{f}\}e^{i\omega t} \qquad \{x(t)\}=\{\mathrm{x}\}e^{i\omega t} \tag{5}$$

其中{f}與[1]為 $N\times 1$ 為與時間無關的頻率域的振幅，則動力方程式可以改寫成

$$\{x\} = ([K] + i\omega[C] - \omega^2[M])^{-1}\{f\} \tag{6}$$

$$\{x\} = [H(\omega)]\{f\} \tag{7}$$

其中 $[H(\omega)]$ 是 $N\times N$結構系統的位移響應矩陣，則多自由度的頻率響應函數通式$H_{p,q}(\omega)$可以表示成

$$H_{p,q}(\omega) = (x_p/f_q) \tag{8}$$

其中，x_p為外力 f 作用在 q 點時結構在 p 點的位移反應轉換成頻率域的振幅。基本上頻率響應函數曲率法(Frequency Response Function Curvature (FRF curvature))是由模態曲率(Mode Shape Curvature Method)延伸而來。頻率響應函數曲率法可以表示為:

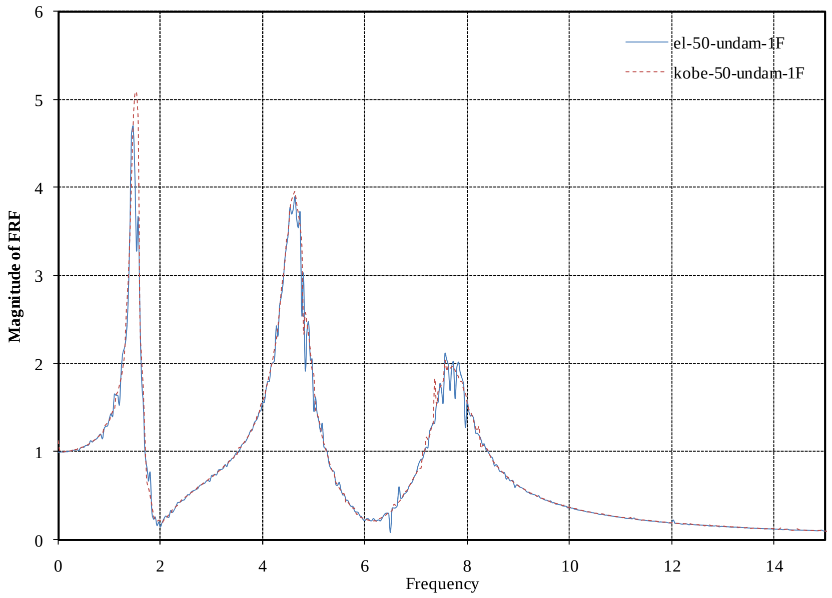
$$\varphi''(\omega)_{i,j} = (\varphi(\omega)_{i+1,j} - 2\varphi(\omega)_{i,j} + \varphi(\omega)_{i-1,j})/h^2 \tag{9}$$

式中 $\varphi(\omega)_{i,j}$ 在位置 i 的 FRF 值對應每個外力輸入位置 j； h 為量測點 i 與 i+1 間的距離。

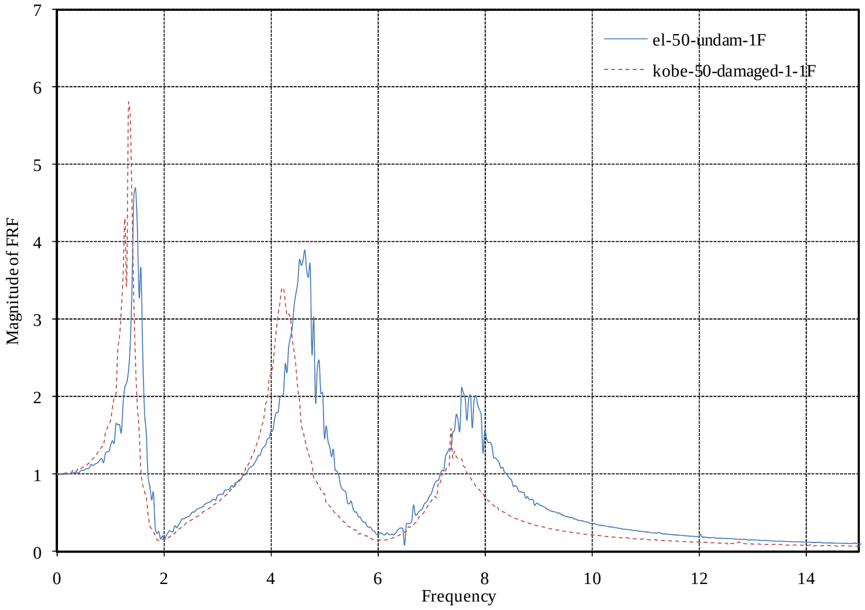
FRF Curvatures 在量測點 i,依所選的頻率的絕對差值為式(10)。

$$ABS(\Delta\varphi''(\omega)_{i,j}) = |\varphi''_U(\omega)_{i,j} - \varphi''_D(\omega)_{i,j}| \tag{10}$$

如圖八所示，當結構在沒壞的狀況下其 FRF 的圖形幾乎是吻合的，而圖九明顯的指出結構破壞前後的狀態。由圖上可以知道即使在不同的外力激勵下，還是可以得到好的偵測結果，該法可以適合用在地震與颶風等天然災害上。

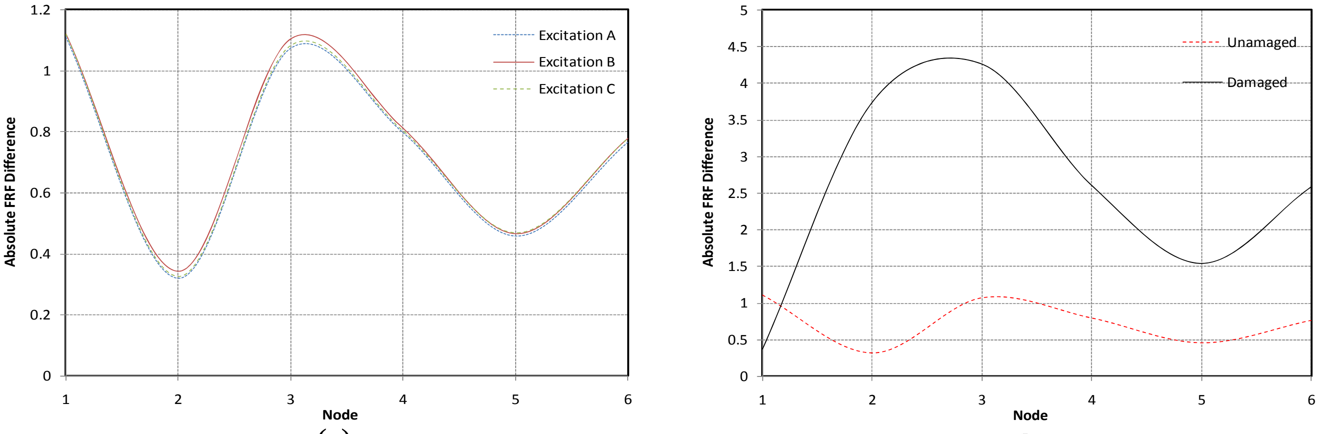


圖八 不同地震外力下三層樓模型的 FRF



圖九 損壞與未損壞之結構之 FRF

利用(10)式，圖十(a)顯示不同外力激勵下完好結構的絕對差值，結果顯示，當結構沒壞的時候即使外力不同，其圖形依然保持相似的狀態。比較圖十(a)和圖十(b)可以很明顯的看到損害的差異。



(a) (b)

圖十 (a) FRF 的絕對差值(結構未損壞) (b) FRF 的絕對差值(結構損壞)

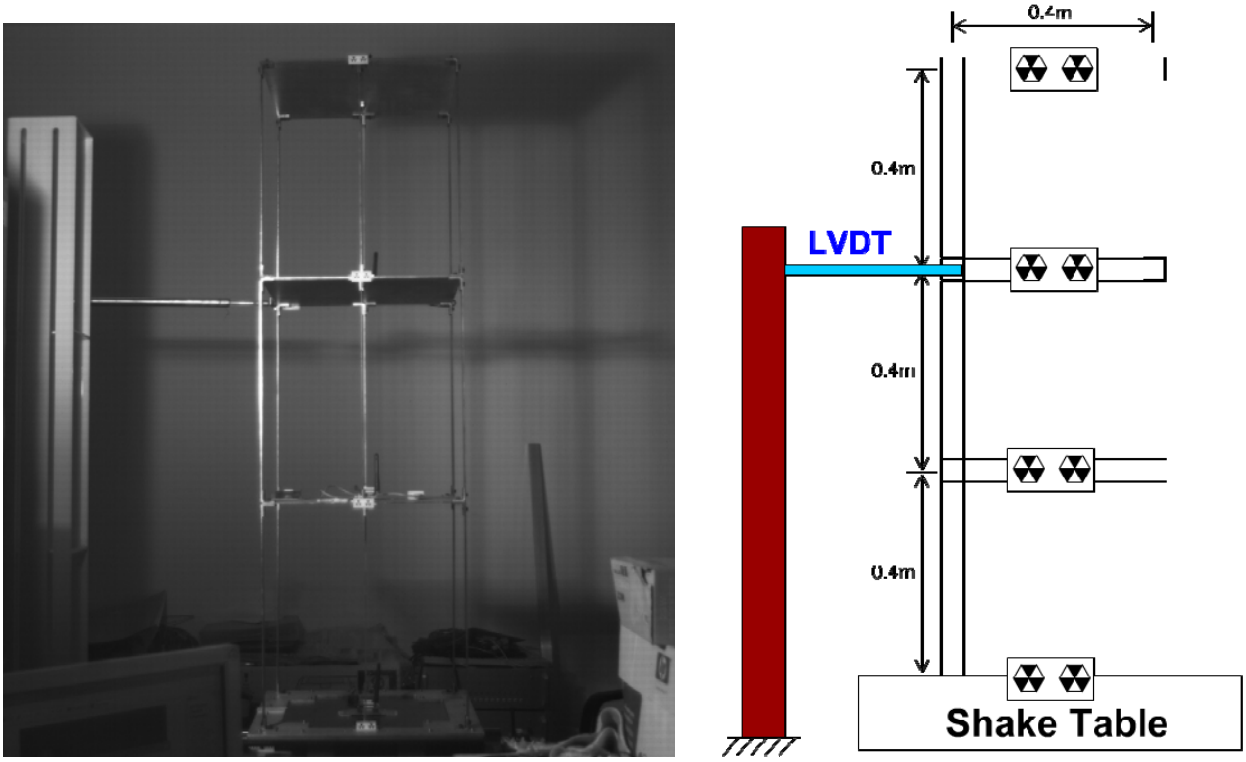
5.4 實驗數據數值分析

本研究依據所發展之數位影像量測系統，進行各種相關實驗以驗證本系統之可行性與效能，分述如下。

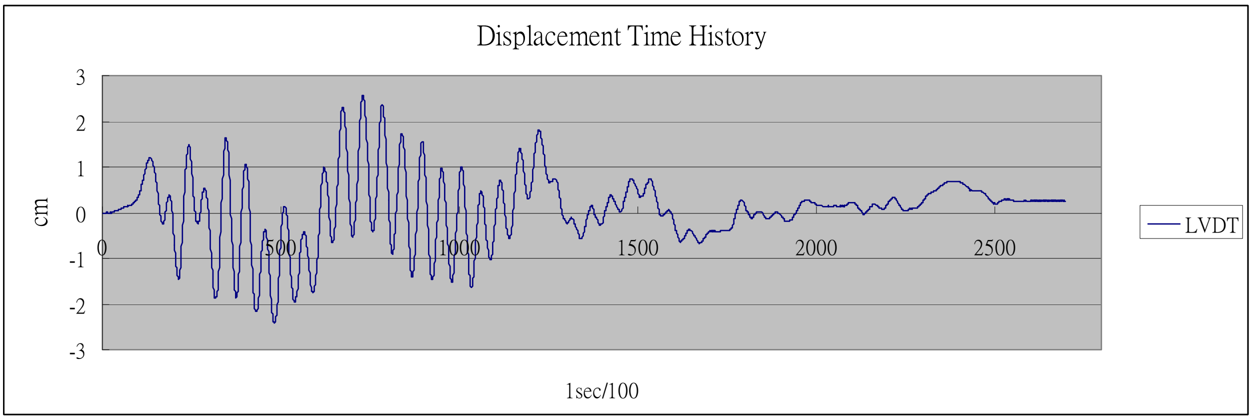
5.4.1 三層樓小型剛構架

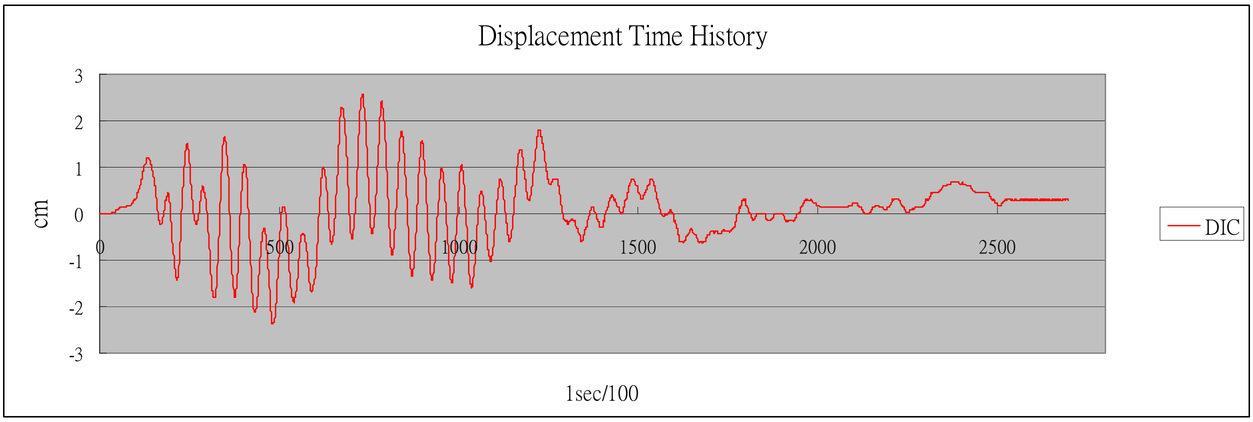
為了初步檢測及驗證本系統，本研究採用一個 1/8 比例之三層樓剛構架，置於小型震

動平台來進行實驗測試。此實驗之振動平台為 Quanser 的 Shake Table II 振動平台，為一個設計優良且具有良好控制界面的實驗震動平台，此剛構架每層質量為 3.8 kg，每一根梁柱之斷面積為 0.8 cm^2 ,每層樓高為 0.4m。圖十二為實驗構架二樓之 LVDT 量測之位移歷時曲線及採用本系統所量測之位移歷時曲線。由圖中可以看出 LVDT 與本系統量測之位移資料，不論是峰值與波形都相當的一致。表一為 LVDT 與本系統量測之各樓層前二個模態頻率之比較，誤差顯示本系統量測結果與 LVDT 量測之模態頻率相當接近，可證明該數位影像實驗量測系統之效能。本次實驗量測所得各樓層位移歷時曲線，顯示於圖十三，為模擬結構損壞造成結構勁度改變，將層間柱變更為勁度較小的柱，量測所得位移歷時曲線如圖十四所示。單純從位移歷時曲線來看，無法清楚判別結構之損壞，但若將訊號經由快速傅立葉轉換後，從時間域的訊號轉換為頻率域的訊號，再利用上述結構損壞評估方法，即可判別出結構已有損壞，而且是損壞在三樓的位置。



圖十一 三層樓剛構架(1/8 比例)

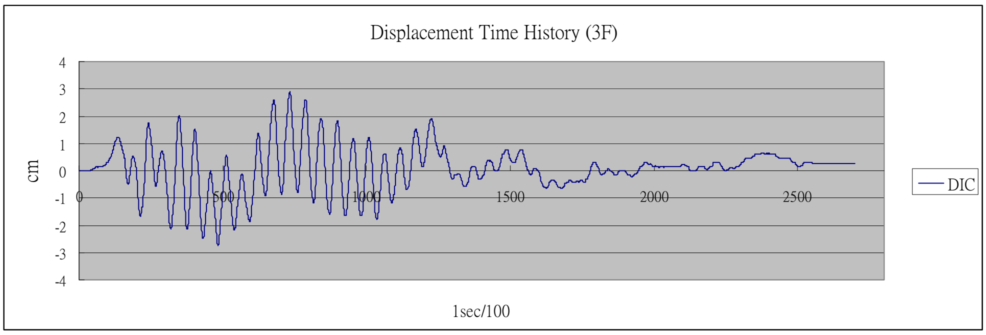


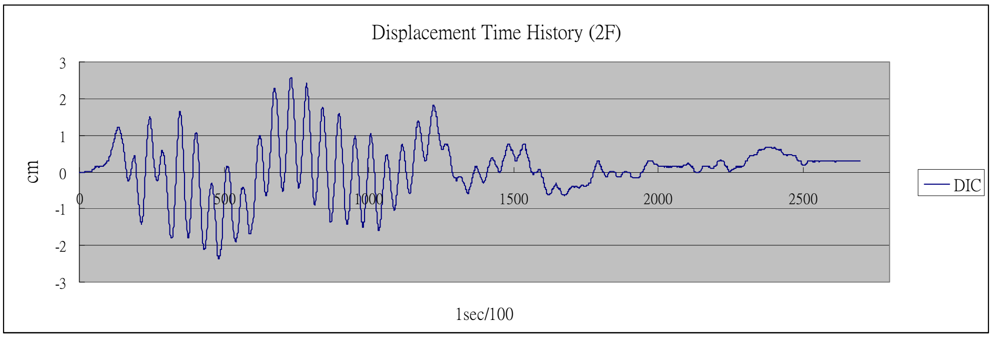


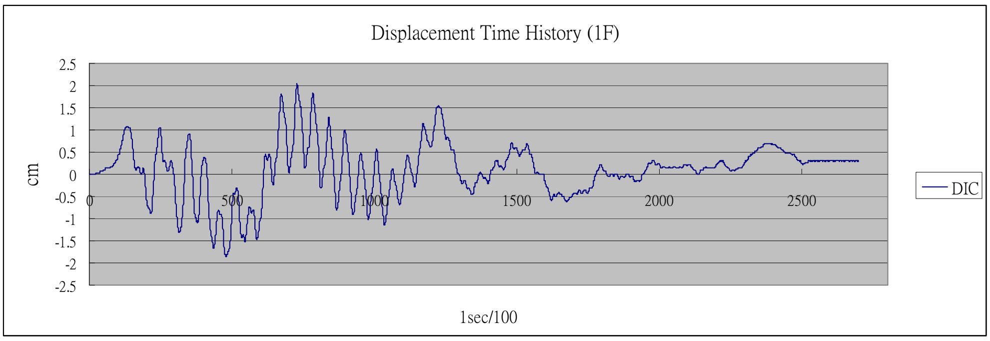
圖十二　LVDT 與數位影像技術量測之位移歷時曲線

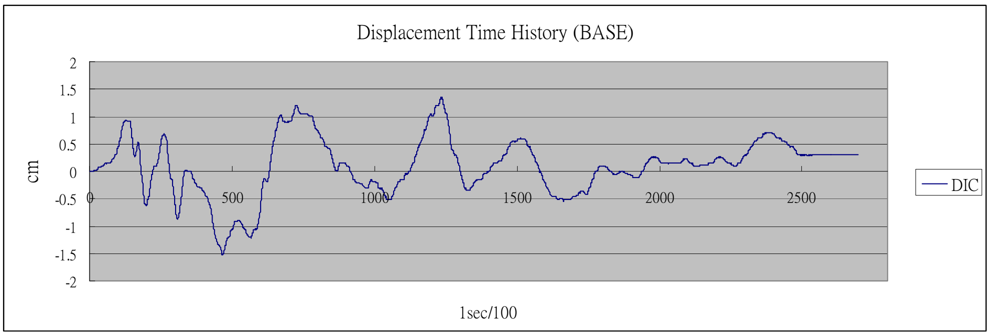
表一 LVDT 與數位影像技術量測各樓層振態頻率比較

樓層別	LVDT	DIC	Error
1st Mode			
1F	-	1.846891	-
2F	1.836331	1.847582	0.6127%
3F	-	1.847654	-
2nd Mode			
1F	-	5.495731	-
2F	5.427729	5.498102	1.2965%
3F	-	5.498521	-

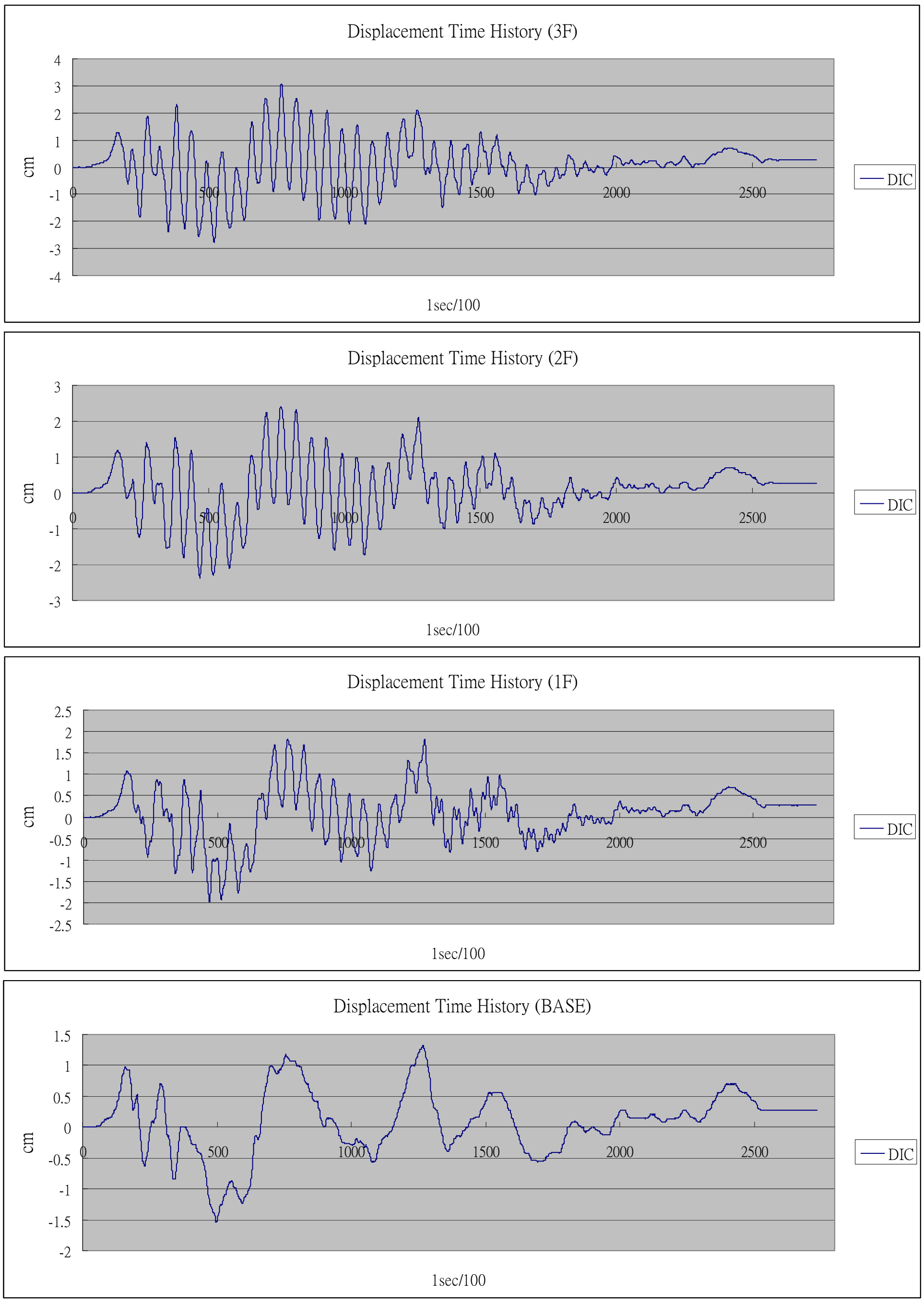








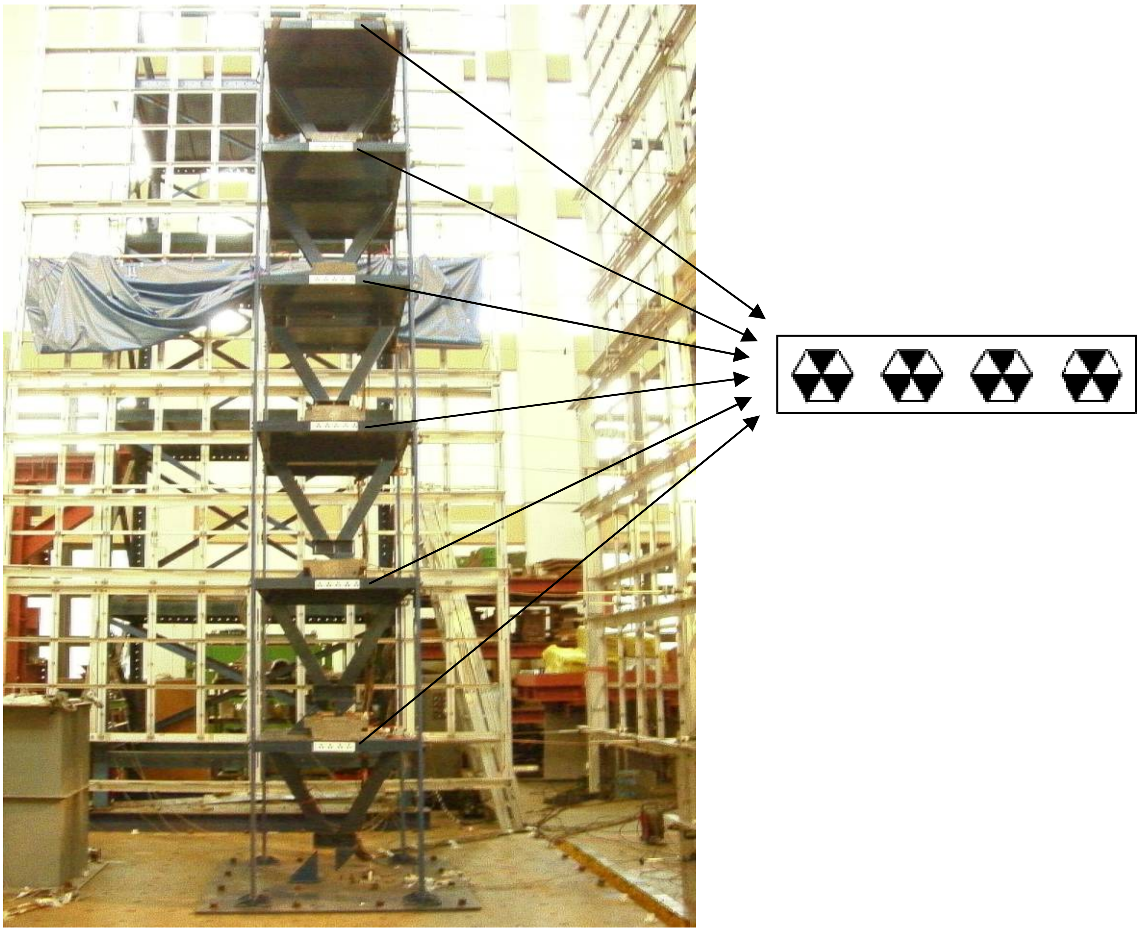
圖十三 正常結構所量測之位移歷時曲線



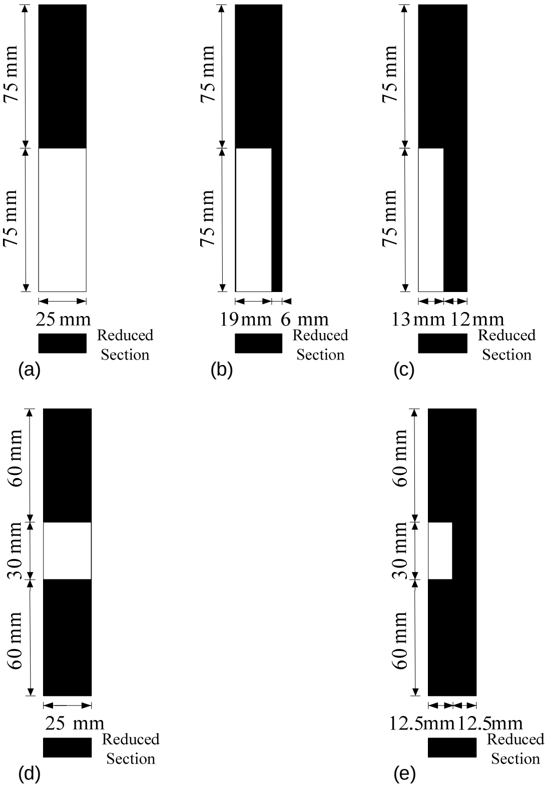
圖十四 三樓層間柱勁度減少所量測之位移歷時曲線

5.4.2 六層樓縮尺結構模型試驗

本研究將所發展的數位影像量測系統於國家地震中心的六層樓結構縮尺模型進行震動台試驗，以確認本量測系統在較大型結構體上之可行性及效能。模型尺寸與蜂巢網格標記佈置之實體構架照片如圖十五所示。結構損害的模擬作法是利用在柱子上切割裂縫，圖十六為損害的斷面圖，損害案例則如表二所示。



圖十五 六層樓鋼構架及蜂巢網格標記佈置圖

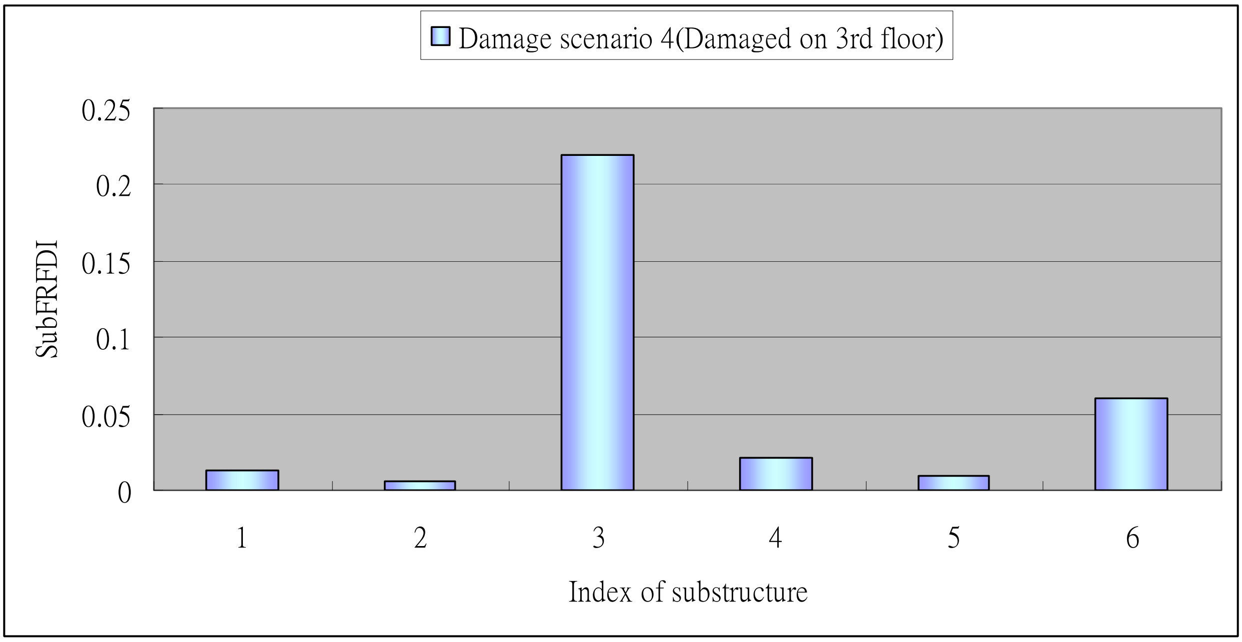


圖十六 損害斷面圖

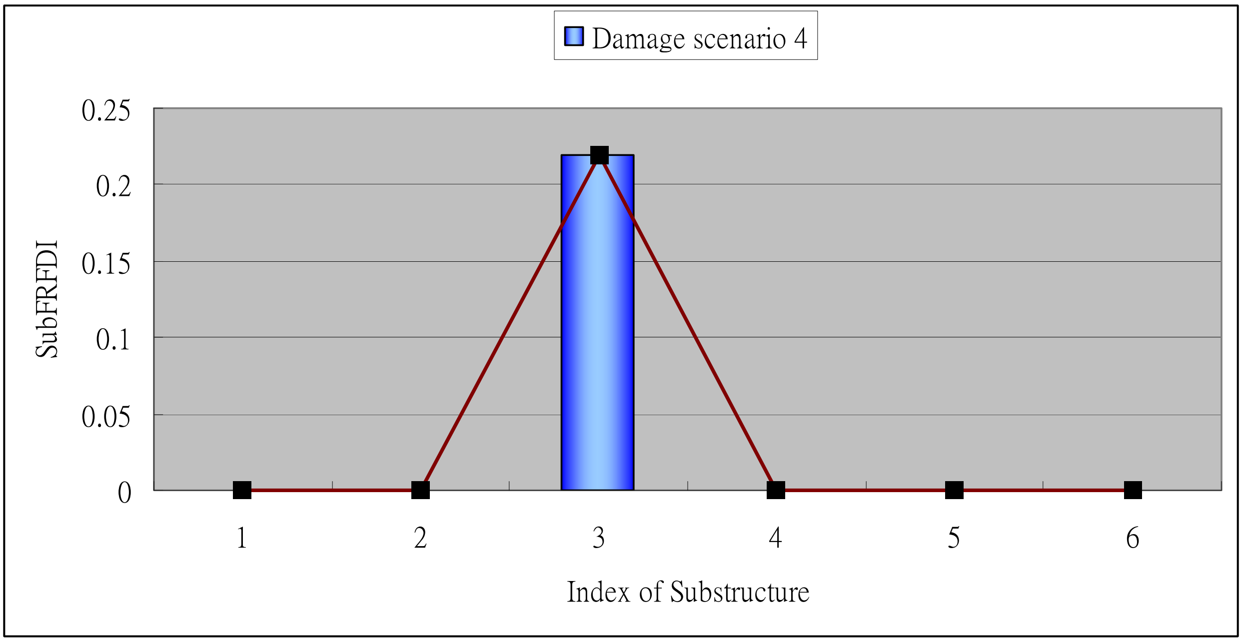
表二 損害案例

Damage scenario case	**Description**
Undamaged scenario case1	Undamaged Structure excited by 100gal *El Centro earthquake input.*
Undamaged scenario case2	Undamaged Structure excited by 50gal *El Centro earthquake input.*
Damage scenario 1	Reduced 3.75 cm width in the medium height of each column at 1st floor excited by 100gal *El Centro earthquake input.*
Damage scenario 2	Reduced 7.5 cm width in the medium height of each column at 1st floor excited by 100gal *El Centro earthquake input.*
Damage scenario 3	Reduced 7.5 cm width and 6mm thickness in the medium height of each column at 1st floor excited by 100gal *El Centro earthquake input.*
Damage scenario 4	Reduced 12 cm width in the medium height of each column at 3rd floor excited by 100gal *El Centro earthquake input.*

利用數位影像相關法量測各樓層受力後之位移歷時，採用 5.3 節的損害評估法可以有效的識別出結構損害的位置。由圖十七可以看出，利用該評估方法可以有效的識別結構損害的樓層，由圖中可以看出最高的指標值出現在 3 的位置，表示該結構於三樓發生損壞。經由資料正規化之後，可以更加清表示損壞的樓層位置，如圖十八所示。



圖十七 結構損害案例評估結果



圖十八 結構損害案例評估結果:正規化後

六　結論

本計畫為一年期之計劃，主要利用數位影相關法及蜂巢網格標記發展一實用之結構實驗量測系統，以應用於結構健康監測之上。目前的研究結果為已可依據高速相機拍攝含蜂巢網格標記之連續影像，分析估算實驗構架在模擬地震作用下所產生之各樓層位移，並能推估至次像素精度以下。本研究採用之高速相機採樣率高達500frame/sec，對於結構破壞瞬間的檢測有一定之優勢，然而由於高速採樣對應的大量儲存資料，在資料傳輸速度有其瓶頸存在，因此在高速採樣下只能盡量擷取較小之影像範圍，以求降低資料量，避免資料嚴重遺漏。除此之外，高速採樣造成的結果是相機快門時間變短，也就是曝光時間變少，因此必須提供足夠的光源於試體上，否則將會降低影像資料解析出來之精確度。初步獲得之量測數據結果，與LVDT有線設備所量測進行比較，數值均方根誤差大約在2%至4%之間，但若將時間序列資料經由FFT轉換至頻率域，在頻域峰值之識別上，則可達到相當高的準確度。因此，本系統之結果確實能夠被應用在結構損壞的識別，進而整合為一套結構健康監測系統。本研究可利用邊緣偵測程式找出蜂巢標記所在位置，以決定各樓層分析位移之參考區塊位置及大小，配合數位影像相關法估算整數像素之位移，再利用像素切割及分析，進一步推估次像素位移，以實現更準確之結構位移量測。此外，本研究已於國內外之結構相關研討會，各發表一篇論文，後續當可持續發展，以求更深入研究數位影像在結構實驗之應用，而在次像素之解析上亦可再強化，以改進實驗數據之精確度，除了加強精度外，也可運用高速平行運算之技術，以進一步加快系統之計算時間。

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國外研討會

[1] Shih-Lin Hung ,and Yung-Chi Lu (2010), The study of combining hive-grid target with sub-pixel analysis for measurement of structural experiment, In Computing in Civil and Building Engineering, Proceedings of the International Conference, W. TIZANI (Editor), 30 June - 2 July, Nottingham, UK, Nottingham University Press.

國內研討會

[1] **陸勇奇**、洪士林，「蜂巢網格標記結合數位影像相關法於結構實驗量測之應用」，98年電子計算機於土木水利工程應用研討會，中華大學。

出席國際學術會議報告

報告人姓名	陸勇奇	報告日期	2010/07/07
系所及年級	土木所博五	核定文號	NSC 98-2221-E-0009-097
連絡電話	0922092686	電子信箱	lukas@thu.edu.tw
會議期間	2010/06/30~2010/07/02	會議地點	英國 諾丁罕 UK Nottingham
會議名稱	（中文） 第十三屆電子計算機在土木工程國際研討會 （英文） 13th International conference on Computing in Civil and Building Engineering		
發表論文題目	（中文） 結合蜂巢網格標記與次像素分析於結構試驗量測之研究 （英文） The study of combining hive-grid target with sub-pixel analysis for measurement of structural experiment		

(一)參加會議經過:

2010 年第十三屆電子計算機在土木工程國際研討會在英國諾丁罕舉行，會議期間為民國九十九年六月三十日至七月二日共計三天，來自世界各地，包括四十個國家、五百三十二位不同的作者及三百零一篇論文，除了土木學術界，也有業界人士及其它領域學者參加。這是我第一次出席國際研討會，也是第一次搭乘十幾個小時的長途飛行旅途，所有交通行程都是自己預先上網查詢，並初略規劃預計搭乘的交通工具及時間。本次旅程搭乘長榮航空飛往倫敦希斯洛機場，中途經泰國曼谷轉機。出發時間為上午九點，加上轉機的時間，大約花費十七個小時才到達倫敦，時差有七個小時，因此到達希斯洛機場的時間大約晚上七點鐘。完成出關手續後，迅速前往地鐵站。由於希斯洛機場並沒有直達諾丁罕的火車，因此必須搭地鐵前往 St. Pancras，再轉搭火車至諾丁罕車站。倫敦的地下鐵四通八達，非常方便也相當快速。由機場到 St. Pancras 大約一個小時的行程，到達 St. Pancras 的地鐵站，即匆匆前往 St. Pancras 火車站購買火車票，英國的票價與台灣非常不一樣。以 St. Pancras 到 Nottingham 而言，單程票價 49.3 英磅，來回票價則是 50.3 英磅，只有相差 1 英磅。這段行程大約二個小時，到達諾丁罕火車站時已經是十一點十五分，因此搭計程車直接前往諾丁罕大學，大約七、八公里花費 8.8 英磅，整體而言英國的交通費用比台灣昂貴許多。後來才知道，如果搭公車只要 1.6 英磅，只是時間已經太晚。計程車到達學校的招待所已經將近十二點，櫃台人員即將下班，但仍順利完成 check-in 手續。本次研討會，主辦單位有開放幾棟宿舍讓與會人員訂房，一個晚上 48 英磅，三天會議期間我都住在學校提供的宿舍。第一天早上註冊後即舉行開幕會議，並由會議主辦單位致詞，及學者論文報告。我是安排在第三天報告，由於第一次出國以英文報告論文，因此一直利用空閒時間練習，以期順利完成英文口頭報告。會議中可以看到來自各國的學生或者學者報告，各有優缺點，也提醒自己在報告時該注意的地方。由於是

第三天的最後一個 session，我又擔心趕不及航班，因此有先行告訴主辦單位，調整順序為第一個報告。報告過程順利完成，但是自己對於問題的回答，並不是很滿意，我想自己還有很多進步的空間，也讓自己更有學習的衝勁，期待未來能更加提昇自己的英語相關能力。這次研討會認識了一些其它學校的老師、學生，像是大陸、日本、韓國不同地方，當然也包括台灣與會人士。在每天會議結束後的晚上空閒時間，自行搭乘公車前往市區走走，看看當地有相當歷史的建築與建設，在這裏似乎大家過得滿悠閒，而不像台灣總是行色匆匆。諾丁罕在英國不算是大城市，因此並沒有看到什麼高樓大廈，路旁看到的小型社區幾乎都是二、三層的傳統建築，即使是辦公大樓，也絕大部份沒有超過十層樓的建築，交通並不會很擁擠，當行人要穿越馬路時，則自行按下紅綠燈按鈕，等待號誌變換，行車規矩非常良好，綠燈的時候不用擔心會有車子衝過來。公車種類很多，從 Nottingham 到市區只要 1.6 英磅，比計程車便宜多了。大街上看起來都很乾淨，相信是一般民眾都很守規矩，不會任意破壞環境，這是值得我們學習的地方。

(二)與會心得:

這次參加這個會議，是我第一次於國外參加的會議，有蠻多心得的。我深深認為多練習一定會較為順利的，這次的報告有一、兩頁不太平順，雖然表現的不是非常完美，但是對於英文口頭報告有了一定的體驗，對於爾後的自信度有了相當的提昇。因此不管有沒有信心講好，都應該有機會出國口頭發表論文，讓自己有機會多增長見聞,除了可以認識各國的專家學者也可以加強自己的國際觀與英文表達能力。另外，在會議中你可以看到各國所做的研究，可以看到有比你差有也比你好的研究。在國外念書的學生，英文普遍來說都不錯，但也會覺得有些並不是那麼的好，我想有可能也是常跟中國學生接觸而少練英文吧。這次出國大大增加了國際觀，也給自己相當多的刺激，除了英文要加強之外，國外學者在學術研究上的嚴謹與系統方法也是值得我們學習的。在與國外唸書的同學聊天後，發現，

在國外的修課與研究壓力，比起台灣真是大巒多的，更加深了我要更加用功與努力的動力。這次難得的體驗讓我對未來研究更加充滿鬥志與熱情，在國際化時代，有機會應當常常踏出國門，讓自己的視野更加的開闊，也可以讓本身的研究與國際接軌。

(三)攜回資料:

一. 論文摘要全集

二. 會議議程

三. 論文摘要及全文電子檔(隨身碟)

(四)結論:

一. 電腦技術在土木工程的應用及整合已是國際土木界重視的研究，包括 Building Information Modeling、Industry Foundation Classes。

二. 此會議乃是資訊技術在土木工程應用交流的重要場合。

三. 此次會議給了學生許多寶貴的經驗，對當前電腦技術應用於土木工程有更深切的體認。

四. 建議讓更多的同學能夠多參與國際學術會議進行報告，以提昇個人國際觀及學術研究國際化。

五. 建議國科會能夠提高補助的金額，減輕學生負擔，以提高出國意願。

六. 多出國報告可以增加國際視野與英文口語溝通能力。

The study of combining hive-grid target with sub-pixel analysis for measurement of structural experiment

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Abstract

This study presents a digital image processing technique, by integrating sub-pixel analysis using digital image correlation method with a novel hive-grid target, for the measurement of structural experiment data. First, a numerical simulation of photography experiment at short range is employed to validate the feasibility of proposed approach. Herein, the simulation image caught from digital speckle and hive-grid target are compared, and the measured time-history displacement of simulation image is computed by the digital image correlation and edge detection methods. The results reveal that, via the digital image correlation method with hive-grid target, the measured time-history displacement at specific position can be analyzed accurately. Following, the experimental data gained from LVDT and digital camera for a six-storey steel frame at National Center for Research on Earthquake Engineering (NCREE) in Taiwan is used to verify the performance of the proposed approach. The measured time-history displacements of the steel frame are converted into frequency domain via Fourier Transform and Wavelet Transform schemes. The results revealed that the relative error between data from LVDT and analyzed data from digital image correlation is below 1% on frequency domain. Herein, the sampling rate of digital camera is lower than LVDT, because high sampling rate led to underexposure and large data storage. The frame rate of common digital camera is about 30 frames/sec nowadays, however the high speed digital camera can overcome this restriction. The limitation of high sampling rate is exposure time and data storage. The experimental results of numerical simulation and shaking table test revealed that digital image correlation method with hive-grid target is accurate in high resolution images.

Keywords: hive-grid target, digital image correlation method, sub-pixel analysis.

1 Introduction

In general, the measurement device is wired device which is installed on structural and connected to data acquisition. It spent much time at initial stage included setting up and configuration. After wireless technology is developed, the measurement work is easier. The measurement data was gained through radio waves, but packet loss and power usage is an issue to be overcome. Nowadays, the digital image analysis technology is used in many different domains and studied in a recent decade. The optical image facility has advanced year by year. The accuracy of image sensor could be improved in using telescope lens, and high frequency of structure could be measured by high speed digital camera.

The digital image processing and analysis which solved alteration of images by computer is usually applied on two dimensional images. The specified target is painted on structure for the digital image processing, and no more things were installed on building or bridge. The digital camera or video recorder acquired images of structure from remote location. The digital image correlation is a common method for solving the variation of images. The image correlation coefficient was calculated, and image displacement was estimated. The sub-pixel analysis can improve the accuracy of result. At last, the measured time-history displacements are calculated and analysed.

2 Method

The study developed a digital image measurement system which included hardware, software and some programs coded by author.

2.1 *Hardware*

The hardware of the digital image measurement system comprises: high speed digital camera (Basler A504kc, sampling rate: 500Hz), camera lens, image acquisition card, high level computer. The digital camera is a color model whose image-type is Bayer Pattern, we need to decode and get suitable gray images. The high level computer equip with Gigabyte i-RAM expansion card for advancing access speed.

The processing and access speed is not fast enough, and the acquisition data will loss in 100Hz sampling rate. So, the lost data is interpolated linearly as compensation. In future, perhaps the array disk of Solid-state Drive can improve the access speed and advance the sampling rate.

2.2 *Software*

The software of the digital image measurement system comprises: the configuration software of digital camera, LabVIEW 8.5 of NI, MATLAB 2007a of Mathworks. The configuration software can deploy the sampling rate and exposure-time for the camera. The LabVIEW used for dynamic image acquisition, Bayer decode, and static image transformation. The MATLABE used for image enhancement, the digital image correlation, and sub-pixel analysis.

2.3 *Coded Program*

The major object of the digital image measurement system is that solving the displacement of structure by using the digital image correlation. The programs have dynamic image acquisition, gray image transformation, image enhancement, structural displacement analysis program, edge detection, frequency analysis program, and so on. The most important program is the structural displacement analysis program. The basic analysis theory is a based image whose displacement is zero. The system calculated the correlation coefficient with the based image(I1) and other image(I2) block.

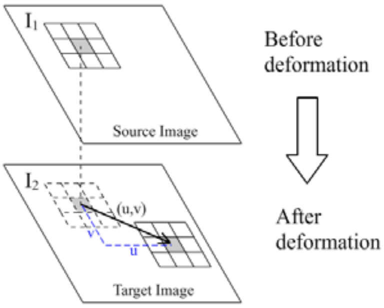

Figure 1. The relation of image deformation.

The formulation of correlation coefficient has many kinds. The paper uses the below equation.

$$C = \frac{\sum\sum\left[\left(f-\langle f\rangle\right)\cdot\left(g-\langle g\rangle\right)\right]}{\left[\sum\sum\left(f-\langle f\rangle\right)^2\cdot\sum\sum\left(g-\langle g\rangle\right)^2\right]^{1/2}} \tag{1}$$

In equation (1), f represented the integer-pixel value of source image, and g indicated the pixel value of target image. Image displacement calculation based on digital correlation coefficient is a kind of searching method to locate target image according to one or more measurements. The precision of measurement unit is integer pixel value. The sub-pixel analysis could improve the precision which stands on the level of analysis. For example, one image block was assigned to f in source image, and another was assigned to g in target image. Assume the correlation coefficient calculated between f and g is 0.95. The block g was moved right 0.1 pixel location as block g'. Their relation between g and g' show in below equation (2).

$$g'_{x,y} = g_{x,y}\times(1-0.1)+g_{x+1,y}\times 0.1 \tag{2}$$

The correlation coefficient between f and g' was calculated afresh. If the result value is greater than 0.95, a new displacement value was assigned. The searching direction kept on moving right to find suitable sub-pixel position. Because the range of gray pixel value belongs between 0 and 255, the precision of 0.1 pixel value was accepted and 0.01 pixel value was not accepted. The level of sub-pixel analysis was divided 0.1, 0.05, 0.025 and 0.0125 in the system.

3 Digital image measurement system

3.1 Image acquirement programming

The LabView software was used in the system for acquiring digital images. The program could be configure sampling rate and stop frame. If the user needs to interrupt for reducing time-consuming, the stop button allowed this function. In order to avoid wasting computer processing time, so the data of images are not compressed and require large disk space. If image resolution is 1024x768 and sampling rate is 100Hz, the data size of 75MB is transferred in per second. The program will meet two problems: 1.data size too large, 2.sampling rate too high caused computing time insufficient. The program will record frames which lost in acquirement procedure. The interpolation method was used to improve the accuracy of time-history data.

When the system completed the images acquirement process, the frames were stored with each single image file. The camera, which is a color machine, needs to decode image for Bayer pattern. Otherwise, the image will display grid line which showed in figure 2.

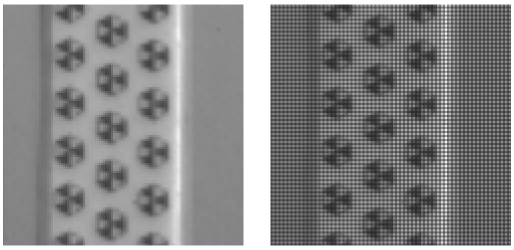

Figure 2. The diference of Bayer decode.(right: not decode)

3.2 System post processing

The MATLAB software was used in this part. First, the image whose brightness is low will be process to enhance image quality. Then, the reference position was located at every floor in the source image. The image block included hive-grid was calculated correlation coefficient and the displacement was gained in 30 pixels. When the displacement was confirmed between integer pixel positions, the sub-pixel analysis was executed. If the correlation coefficient was not maximal between integer pixel positions, the maximum value would be found in sub-pixel. In sub-pixel processing, the system tried to calculate from two directions. If no more maximal value was found, the integer pixel value was estimated as displacement. The sub-pixel analysis could not be segmented unlimited, because the grayscale image had only 256 different intensities.

The unit of image displacement was integer pixel value in the beginning. The calculation of actual structural displacement needed to multiply by a constant proportion s. Then, the measured time-history displacements would be estimated. The constant proportion s could be evaluated by using edge detection to find the edge of hive-grid target. The length of hive-grid target had known. The constant proportion s was calculated simply.

4 Results and analysis

4.1 Numerical simulation result

The study created a numerical simulation image which included digital random speckle and hive-grid target. The images generated from PHP web language had about 600 frames. The variation of images was similar to sine curve. These images were loaded into FLASH as animation. The animation was played in screen, and the time-history displacement was found. The results were shown in figure 3. The time-history displacement calculated by using hive-grid target was smoother than that calculated by using digital random speckle. In the example considered in this study, it shown that the result of using hive-grid target was better than digital random speckle.

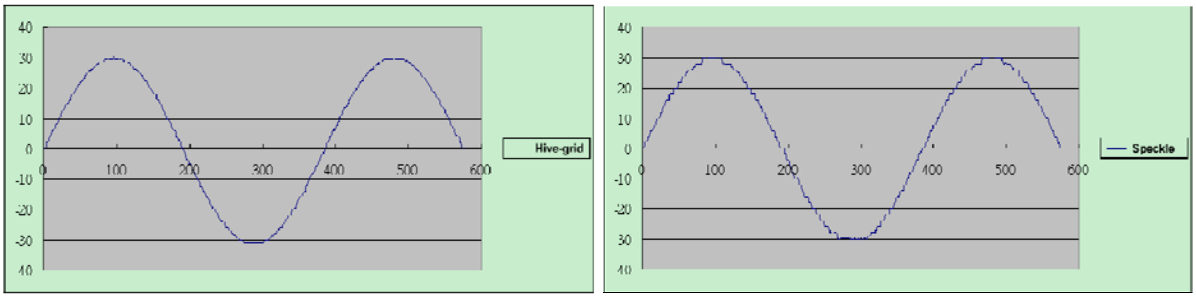

Figure 3. The time-history displacement of the numerical simulation.

4.2 The result of small earthquake simulation

The structural sample, shown in figure 4, is a small three story frame. The experiment base was a small shaker and a LVDT was set on the second floor. The El Centro earthquake was generated from the small shaker, and the time-history displacement was estimated from the digital image measurement system. The results were shown in figure 5 and the curves were very similar. The peak value of frequency calculated in FFT was very approximate.

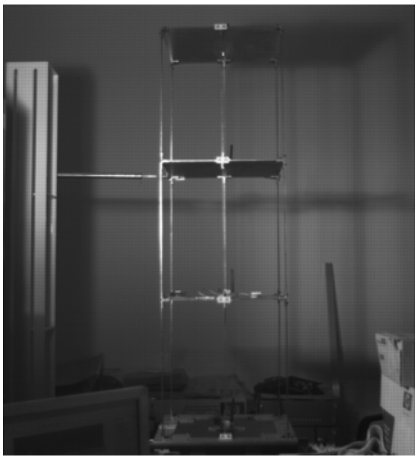

Figure 4. The configuration of small space frame.

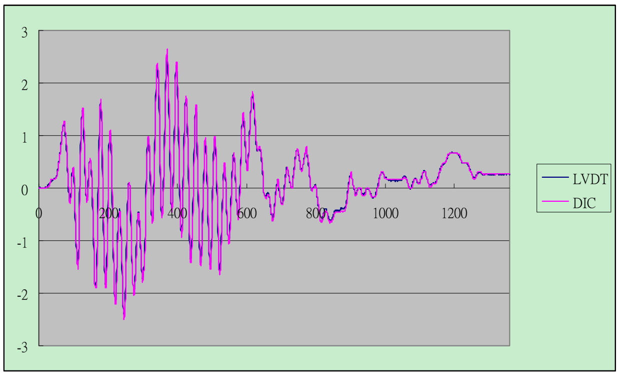

Figure 5. The time-history displacement of small space frame.

4.3 The result of large earthquake simulation

The structural sample, shown in figure 6, is a six story steel frame. The specification of steel frame is: a)cross section of column is 150x25mm, b)column height is 1000mm, c)floor slab is 1000x1500x20mm, d)weight is 75kgw x 6, e)beam is 50x50x50mm. The experiment was tested at NCREE in Taiwan. The earthquake magnitude included 50, 100, 500, 1000, and 1500 gal. The displacement estimated by the digital image measurement system had higher error in low floor and low magnitude. The result, shown in figure 7, had better accuracy in high floor or high magnitude. The peak value of frequency calculated in FFT had about 1% error.

5 Conclusions

The digital image measurement system is a feasible option in this study. The time-history displacement estimated by the digital image system was very similar to LVDT in some experiment. The curves, shown in figure 5, overlapped almost in all period. The curves, shown in figure 7, had similar trend, but there are not accurate. The actual length of one pixel was presented in proportion value s. If s is large, the image is rough; if s is small, the image is detailed. By using sub-pixel analysis, the system would advance the accuracy to 0.1 pixel value. So, if s is smaller than 0.1mm, the accuracy will achieve 0.01mm easily. In this paper, three conclusions were made from these experiments.

1. In higher resolution, the time-history displacement shows very similar result. In lower resolution, the displacement trend is approximate, but the accuracy of displacement is too large. The digital image measurement system could be applied in estimating displacement of structural test in higher resolution.

2. The set-up of image measurement system is very easy, and it is very serviceable scheme.

3. The measurement of hive-grid target length could cause error, and therefore many hive-grid targets were measured to diminish error.

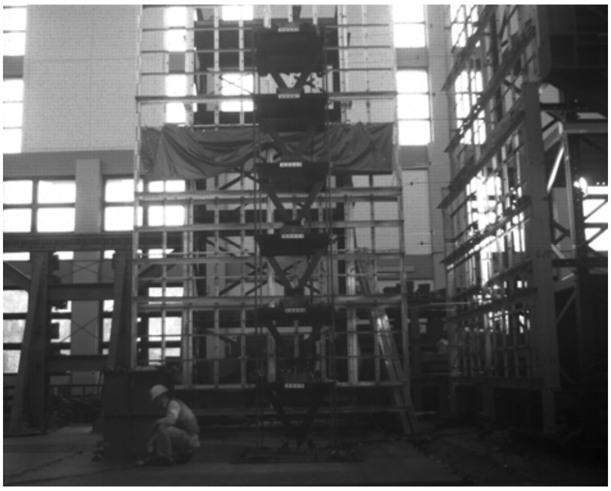

Figure 6. The configuration of six story steel frame.

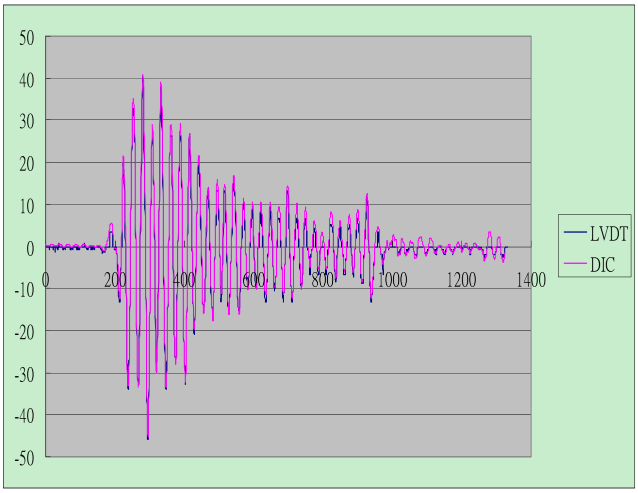

Figure 7. The time-history displacement of top floor at 100 gal.

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出席國際學術會議報告

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會議名稱	（中文） 第五屆世界結構控制和監測研討會 （英文） 5th world conference on structural control and monitoring		
發表論文題目	（中文） 能量擷取在結構健康監測上的應用 （英文） Study of Energy Harvesting Technology in Structural Health Monitoring		

(一)參加會議經過:

2010年結構控制和監測研討會在日本東京舉行，會議期間為民國2010年年7月12-14日。世界各國，共有上百人的學術界與業界人士參加。第一天就是註冊與茶會，認識了一些老師與學生，第二天開始就是正式的會議發表，我是排在第二天。由於我是第四次出國以英文報告論文，因此還蠻駕輕就熟，但是到日本後，還是一直利用空閒時間練習，在會議中你可以看到各國的學生或是老師報告，各有優缺點。在我報告的時候還算順利，別人的提問我也都還答得出來。表現應該還算不錯了。可是自己知道，還有很大的進步空間，尤其是在發音與最後的問答方面，還需要多加強。這次研討會也認識了蠻多大陸去的學者，感覺在大陸在派遣學生或是學者出國參加研討會方面是相當的積極,台灣其實也應該更鼓勵與贊助學者與學生出國參加國際研討會為台灣發聲,這也是我們需要再努力與加油的。

(二)與會心得:

這次參加這個會議，是我第四次於國外參加的會議，有蠻多心得的。在會議中你可以看到各國所做的研究，可以看到有比你差有也比你好的研究。在國外念書的學生，英文普遍來說都不錯，但也會覺得有些並不是那麼的好。這次出國大大增加了國際觀，也給自己相當多的刺激，除了英文要加強之外，國外做研究的嚴謹與方法也是我要學習的。在與國外唸書的同學聊天後，發現，在國外的修課與研究壓力，比起台灣真是大蠻多的，更加深了我要更加用功與努力的動力。這次的經驗讓我對研究更加充滿鬥志與熱情，在國際化時代，有機會一定要常常踏出去，讓自己的視野更加的開闊，也可以讓研究與世界接軌。

(三)建議

這次能夠參加這次的研討會，很感謝國科會的經費補助，讓我能夠到國外去發表,建議國科會以後能夠讓更多的同學出去看看,相信對未來一定有相當的幫助。

(四)攜回資料:

論文摘要全集

會議議程

論文摘要及全文電子檔(隨身碟)

(五)結論:

智慧結構健康監測已是國際土木界重視的研究。

此會議乃是結構健康監測在土木工程應用交流的重要場合。

此次會議給了學生許多寶貴的經驗。

建議讓更多的同學能夠出國報告。

STUDY OF ENERGY HARVESTING TECHNOLOGY IN STRUCTURAL HEALTH MONITORING

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Abstract

Structural health monitoring (SHM) of buildings and civil infrastructures has recently received increasing attention. Developing a real time monitoring system with low cost, high stability and robustness is important. The aims of SHM are to monitor health condition of structure long term using smart sensor system. Most existing SHM system use wired monitoring systems to collect structural response data from various locations in the structure for analysis. However, installing a large scale wired monitoring system is time consuming and often takes high maintenance and deployment costs. A wireless sensor network based monitoring system provides many benefits such as flexibility of deployment, low maintenance cost, low power, self-organization and wireless communication. Therefore, the wireless sensor networks based wireless monitoring system is considered an appropriate choice for developing an intelligent structural health monitoring system. However, power sources and power consumption are the critical issue if batteries have to be periodically replaced. This study introduced general theory of vibration-based energy harvesting method. An improved piezoelectric harvesting model with new energy harvesting IC, LTC3588-1 (LINEAR TECHNOLOGY) was also demonstrated. Experimental studies were conducted in both laboratory and full-scale structures. This study further proposed a windmill-magnet integrated piezoelectric energy harvesting system. Different piezoelectric materials were evaluated. Experimental results provide an evident that the proposed windmill-magnet integrated piezoelectric energy harvesting system gives high and regular output voltage. Hence the efficiency of energy harvesting in civil structure can be improved. This study will increase our understanding of the energy limitation on wireless sensor networks, and it provides the information of harvesting the ambient energy to wireless sensor device in structural health monitoring.

Introduction

To monitor and control the responses of buildings and civil infrastructures in real time has been increasingly more important. Therefore, to develop a low cost, high stability and more advanced monitoring system is important now. Due to many advantages like smaller size, low power, lower manufacturing costs, self-organization and wireless communication, the wireless sensor monitoring system become an appropriate choice for developing an intelligent civil infrastructures monitoring system (Akyildiz et al. 2002; Du et al. 2005; Mainwaring et al. 2002). Several researches have been devoted to apply wireless sensor network in civil infrastructures monitoring. For example, (Kurata et al. 2003) discussed using a smart sensor based MICA mote platform to monitor risk of buildings for natural and man-made hazards. The performance of the MICA mote was investigated through shaking table tests of a two story steel structure. Lynch et al.(Lynch et al. 2004) designed an active wireless sensing unit that could input excitations into a structural system and proposed a computational framework for analyzing piezoelectric based active sensor signals for indications of structural damage. Wisden (Paek et al. 2005) that was designed for structural health monitoring, can measure tri-axial structural vibration data reliably across multiple hops with low latencies for sampling rates up to 200Hz.

Although a wireless sensor network based structural health monitoring system has many benefits, power sources and power consumption are the critical issue if batteries have to be periodically replaced. Therefore, harvesting and storing the ambient sources of energy to supply the sensor node seems to be an agreeable approach. The sources of ambient energies typically include thermal, sunlight, wind, RF and vibration energy. This study only considered the vibration based piezoelectric energy harvesting approach. Several researches proposing and reviewing the possible energy harvesting schemes can be found in the literature (Beeby et al. 2006; Gratzel 2005; Ottman et al. 2002; Sodano et al. 2007). Several researchers (Anderson and Sexton ; Glynne-Jones et al. 2004; Roundy and Wright 2004) evaluated piezoelectric energy harvesting device on machine or motor. The reason is the regular high frequency vibration of structure such as machine or motor can give maximum efficiency of energy harvesting. However, the low frequency vibration of civil structure such as bridge limits the efficiency of energy harvesting. This study introduced general theory of vibration-based energy harvesting method. An improved piezoelectric harvesting model with new energy harvesting IC, LTC3588-1 (*LINEAR TECHNOLOGY*) was also demonstrated. Experimental studies were conducted in both laboratory and full-scale structures. This study further proposed a windmill-magnet integrated piezoelectric energy harvesting system. Different piezoelectric materials were evaluated. Experimental results provide an evident that the proposed windmill-magnet integrated piezoelectric energy harvesting system gives high and regular output voltage. Hence the efficiency of energy harvesting in civil structure can be improved.

General theory of vibration-based energy harvesting method

A single degree of freedom lumped spring mass system is mostly utilized to model a vibration-based energy harvesting system. A diagram of a piezoelectric cantilever beam with a proof mass at the end and a model of equivalent lumped spring mass system is shown in Fig. 1. The equation of motion of a single degree of freedom (SDOF) system consisting of a mass m, a spring with spring constant k, and a damping coefficient c under external excitation is described as

$$m\ddot{z}(t)+c\dot{z}(t)+kz(t)=-m\ddot{y}(t) \tag{1}$$

where z= x-y is the net displacement. Assuming that the external excitation is harmonic given as $y(t)=Y\sin\left(\omega t\right)$, the steady –state solution for the mass displacement is given by

$$z(t)=\frac{\left(\frac{\omega}{\omega_n}\right)^2}{\sqrt{\left(1-\left(\frac{\omega}{\omega_n}\right)^2\right)^2+\left(2\xi\frac{\omega}{\omega_n}\right)^2}}Y\sin\left(\omega t-\phi\right) \tag{2}$$

where the ϕ is the phase angle given by

$$\phi=\tan^{-1}\left(\frac{\omega c}{k-\omega^2 m}\right) \tag{3}$$

The approximate mechanical power of a piezoelectric generator can be given by

$$P = \frac{m\xi Y^2 \left(\frac{\omega}{\omega_n}\right)^3 \omega^3}{\left[\left(1-\left(\frac{\omega}{\omega_n}\right)^2\right)^2 + \left(2\xi\frac{\omega}{\omega_n}\right)^2\right]} \tag{4}$$

The maximum energy can be extracted by setting the excitation frequency to match the natural frequency of the system and is given by

$$P = \frac{mY^2\omega_n{}^3}{4\xi} \tag{5}$$

Observing Eq. (x), it provides evidence that power can be optimized by lowering damping, increasing natural frequency, mass, and amplitude of excitation.

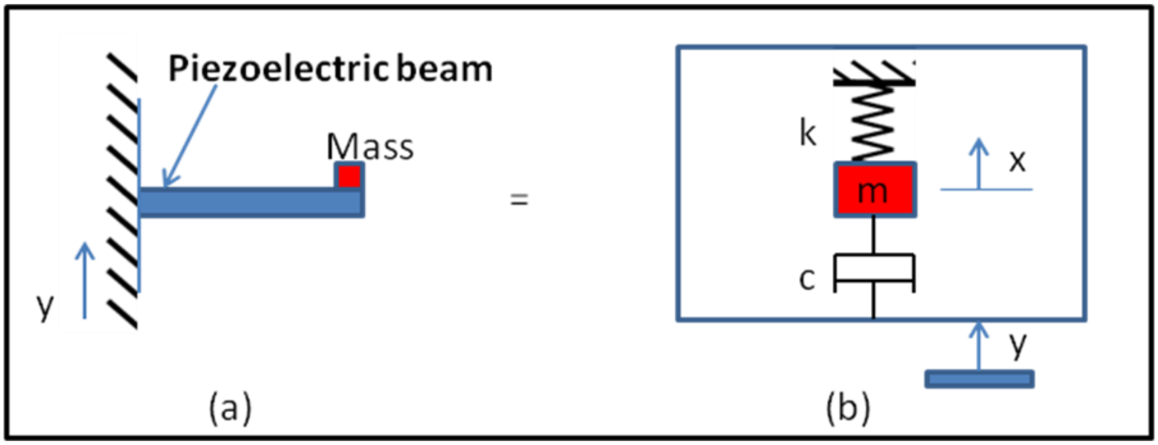

Figure 1. (a) Cantilever beam with tip mass, (b) model of equivalent lumped spring mass system

Energy Harvesting Circuits

A typical energy harvesting circuit, with piezoelectric generator, battery and sensor, is shown in Fig. 2. The piezoelectric material produces an ac voltage output when the piezoelectric deformed. Therefore, this voltage needs to be converted to a dc voltage before charging the capacitor. The four diodes form a bridge circuit to perform a rectifier. Energy harvesters typically produce small amounts of energy over long periods, therefore an energy storage component in the form of a supercapacitor usually contain in harvesters system. A larger capacitor provides power for a longer time for the same load but takes more time to charge it. Typical supercapacitor often has a much lower voltage than standard electrolytic capacitors, a zener diode usually used to prevent the voltage across the supercapacitor from increasing beyond its maximum voltage rating. When applying a load, the supercapacitor discharging immediately, and the voltage across the supercapacitor starts dropping. Hence, a dc/dc-voltage-converter IC is use to assurance a fixed voltage at the output.

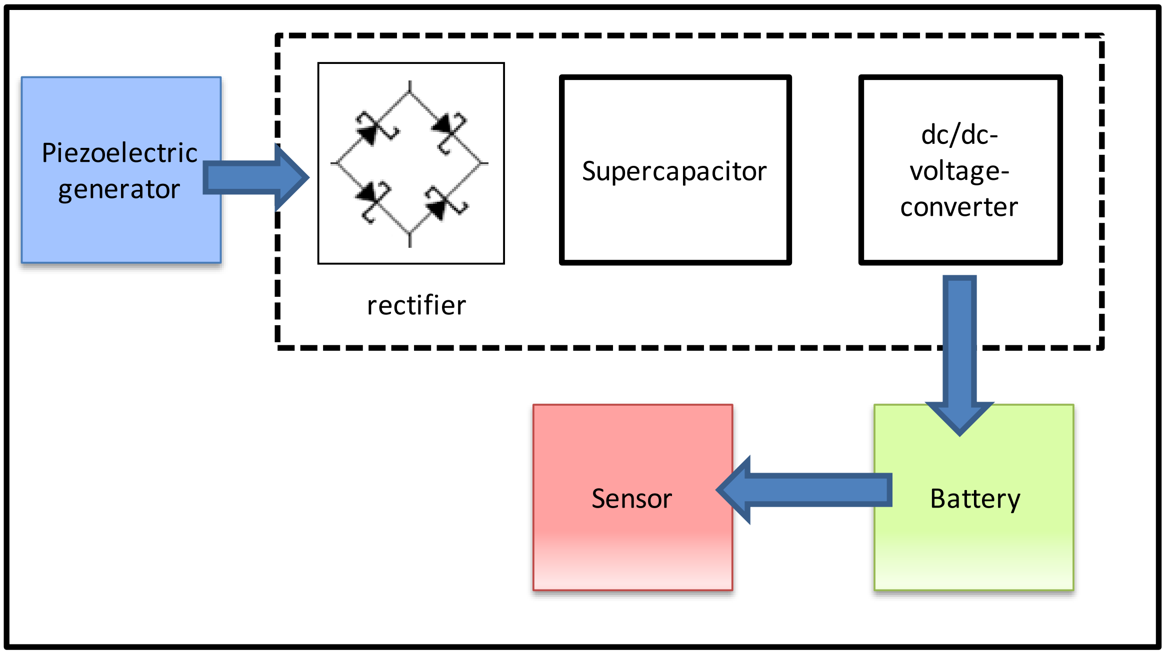

Figure 2. Typical piezoelectric harvesting circuit

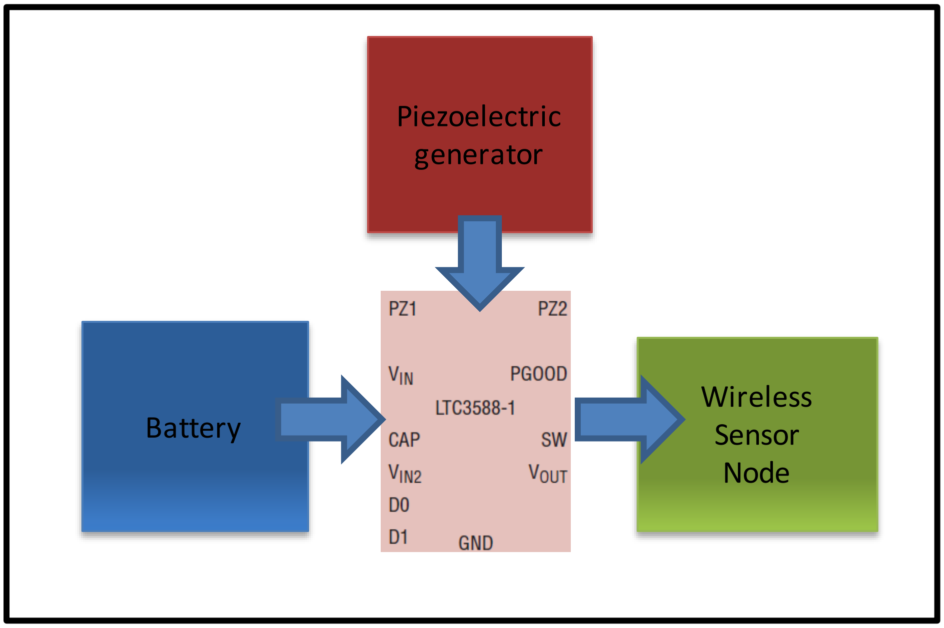

Figure 3. Architecture of energy harvesting based wireless sensor node

The typical piezoelectric harvesting model can be improved via new energy harvesting IC, LTC3588-1 (*LINEAR TECHNOLOGY*). This IC combines a low-loss full-wave bridge rectifier with a high efficiency buck converter to form a tiny energy harvesting component for an ambient energy harvesting. The peak load currents are much higher than a piezoelectric generator can produce. Thus the LTC3588-1 accumulates energy that released to the load to supply the sensor or controller. For the different purpose of applications, this IC provides four output voltages, 1.8V, 2.5V, 3.3V and 3.6V via two selectable pins. Typically, up to 100mA of continuous output current can be provided; however, a higher output current can be supplied by way of sizing the output capacitor. Base on this advanced energy harvesting IC, the architecture of energy harvesting based wireless sensor node was shown in Fig. 3. A LTC3588-1 connects with piezoelectric generator and backup battery to supply the sensor. This architecture proposed that when ambient energy is obtainable, the battery is unloaded, but when the ambient source ceases, the battery initiates and serves as the backup power supply. The backup battery must connect with a series blocking diode connected to VIN pin to prevent reverse current flowing into the battery. Any stack of batteries can be used as long as the battery voltage does not exceed 18V. One should be considered that the peak voltage of piezoelectric generator should exceed the battery voltage. This approach not only decreases the replacing time of battery, but it also improves reliability and elasticity sensing system. For instance, an energy harvesting sensor node is deployed on a structure such as a bridge, may gather energy when the vehicles pass through the bridge. However, in off-peak times the vehicles are rarely and vibration is also low, a battery backup still supplies the sensor node.

Windmill-Magnet Integrated Piezoelectric Energy Harvesting System

Most researchers tested piezoelectric energy harvesting device on machine or motor. The reason is the regular high frequency vibration of structure such as machine or motor can give maximum efficiency of energy harvesting. However, the low frequency vibration of civil structure such as bridge limits the energy harvesting efficiency. Therefore, this study proposed a scheme to solve this barrier. In first stage, the idea is to transfer the rotation of windmill to vertical vibrate the piezoelectric beam for energy harvesting. The proposed simple concept is shown in Fig. 4. Three piezoelectric materials were tested with the proposed concept.

Table 1.Different types of piezoelectric product

Type	Dimension(length X width)	Manufacturing Company
PZT	60X20mm	APC
MFC	85X28mm	Smart Material
Raw Volture	100X25.4mm	MIDE

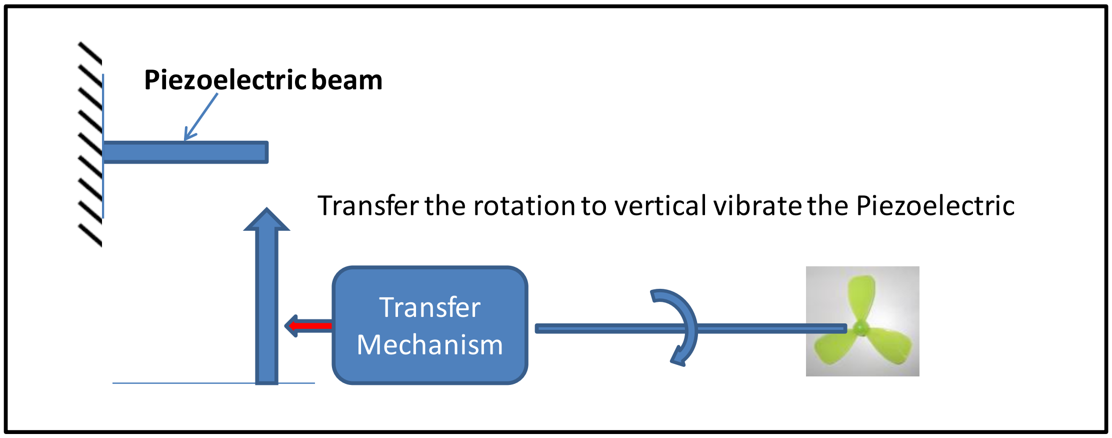

Figure 4. Schematic diagram of windmill based piezoelectric harvesting system

Fig. 5 shows the experimental setup on overpass in Tokyo University. A piezoelectric film was set as a cantilever beam mounted on a base which was fixed in the bridge. Wind can drive the windmill to beat the piezoelectric film to output the voltage. Different piezoelectric materials were evaluated shown ib table1.The Fig. 6 to 8 illustrates the output voltage of PZT, MFC and Raw Volture respectively. As shown in figure, the peak voltage represents the high voltage output when the windmill beat the beam. The result also shows the MFC has high voltage under the same excitation. The result confirms that the proposed windmill based piezoelectric energy harvesting concept is practical. However, contact between windmill and piezoelectric beam might stop the whirling of blade. This study further proposed a windmill-magnet integrated piezoelectric energy harvesting system shown in Fig. 9. MFC was chosen as a result of its high flexibility. A magnet was bonded on the tip of MFC beam as a mass. A windmill was placed in proper distance from the MFC beam and each blade was attached a magnet. When wind drove the windmill, the magnetic force between the piezoelectric beam and windmill can force the beam to vibrate. Fig. 10 provides an evident that the proposed windmill-magnet integrated piezoelectric energy harvesting system gives high and regular output voltage. Hence the efficiency of energy harvesting in civil structure can be improved. Moreover, this system can be integrated with wind turbine and solar panel to form the multi-harvesting energy design.

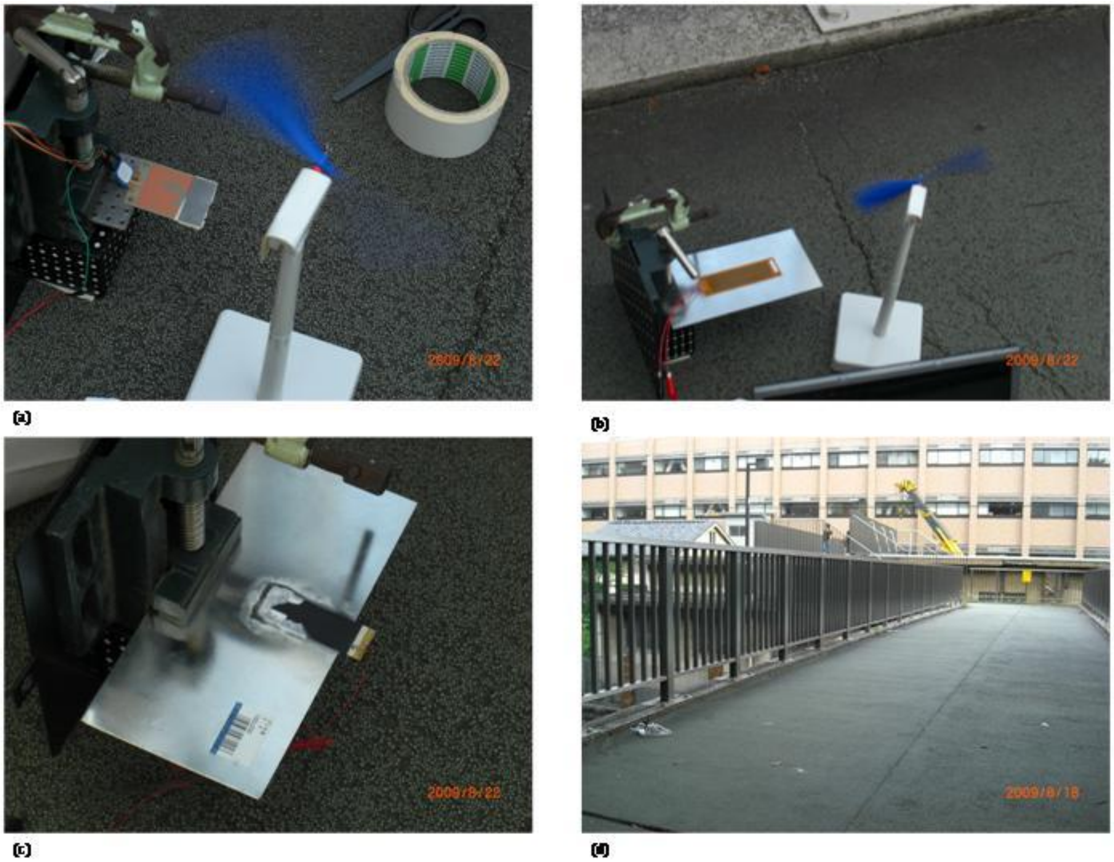

Figure 5. Experiment setup of windmill based piezoelectric harvesting system: (a) Raw Volture, (b)MFC, (c)PZT, (d) Overpass in Tokyo University.

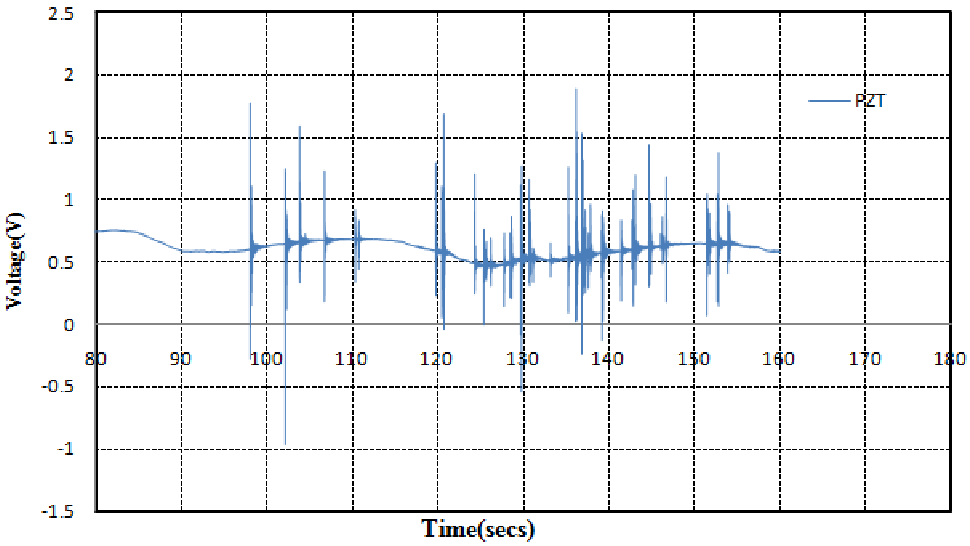

Figure 6. Output voltage of PZT

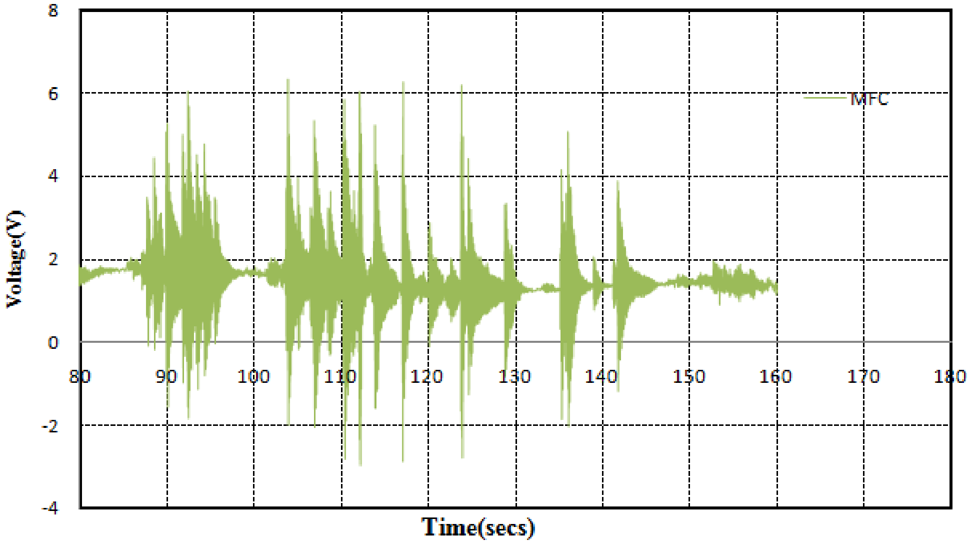

Figure 7. Output voltage of MFC

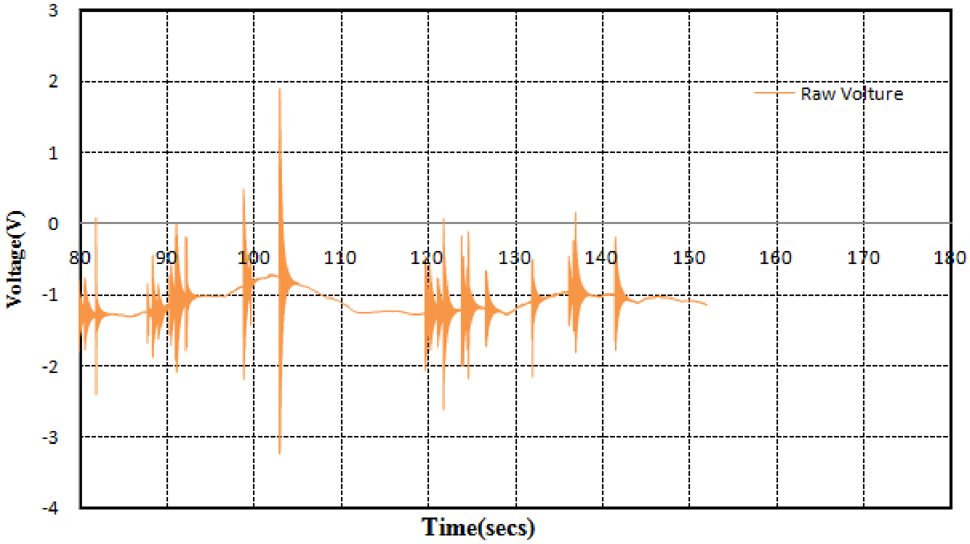

Figure 8. Output voltage of Raw Volture

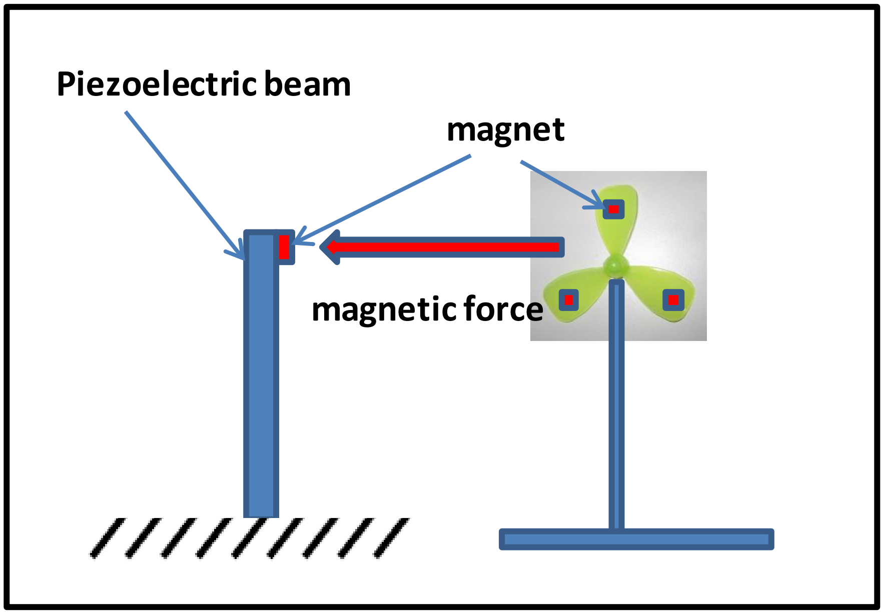

Figure 9. Windmill-magnet integrated piezoelectric energy harvesting system

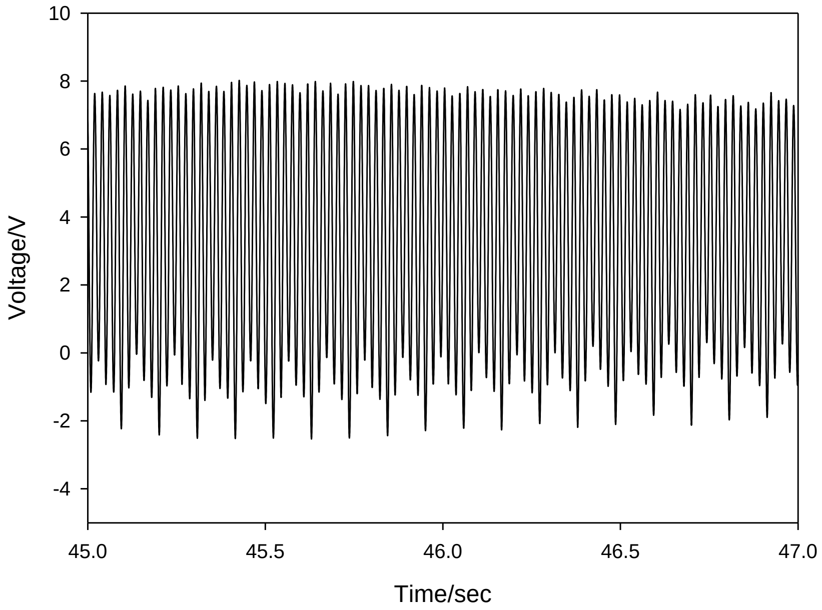

Figure 10. Output voltage of MFC with Windmill-magnet integrated piezoelectric energy harvesting system

Conclusions

This study introduced general theory of vibration-based energy harvesting method. An improved piezoelectric harvesting model with new energy harvesting IC, LTC3588-1 (LINEAR TECHNOLOGY) was also demonstrated. Experimental studies were conducted in both laboratory and full-scale structures. This study further proposed a windmill-magnet integrated piezoelectric energy harvesting system. Different piezoelectric materials were evaluated. Experimental results provide an evident that the proposed windmill-magnet integrated piezoelectric energy harvesting system gives high and regular output voltage. Hence the efficiency of energy harvesting in civil structure can be improved. Moreover, this system can be integrated with wind turbine and solar panel to form the multi-harvesting energy design.

Acknowledgements

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國科會補助計畫衍生研發成果推廣資料表

日期:2010/11/03

國科會補助計畫	計畫名稱：基於數位影像識別技術之結構健康監測系統之研究
	計畫主持人：洪士林
	計畫編號：98-2221-E-009-097- 學門領域：結構應力

無研發成果推廣資料

98 年度專題研究計畫研究成果彙整表

計畫主持人：洪士林 **計畫編號：**98-2221-E-009-097-

計畫名稱：基於數位影像識別技術之結構健康監測系統之研究

成果項目			量化			單位	備註（質化說明：如數個計畫共同成果、成果列為該期刊之封面故事...等）
			實際已達成數（被接受或已發表）	預期總達成數(含實際已達成數)	本計畫實際貢獻百分比		
國內	論文著作	期刊論文	0	0	50%	篇	
		研究報告/技術報告	0	0	100%		
		研討會論文	0	2	100%		
		專書	0	0	100%		
	專利	申請中件數	0	0	100%	件	
		已獲得件數	0	0	100%		
	技術移轉	件數	0	0	100%	件	
		權利金	0	0	100%	千元	
	參與計畫人力（本國籍）	碩士生	0	0	100%	人次	
		博士生	0	2	100%		
		博士後研究員	0	0	100%		
		專任助理	0	0	100%		
國外	論文著作	期刊論文	0	1	70%	篇	
		研究報告/技術報告	0	0	100%		
		研討會論文	0	2	100%		
		專書	0	0	100%	章/本	
	專利	申請中件數	0	0	100%	件	
		已獲得件數	0	0	100%		
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		博士後研究員	0	0	100%		
		專任助理	0	0	100%		

其他成果 (無法以量化表達之成果如辦理學術活動、獲得獎項、重要國際合作、研究成果國際影響力及其他協助產業技術發展之具體效益事項等，請以文字敘述填列。)	無

🟥	成果項目	量化	名稱或內容性質簡述
科教處計畫加填項目	測驗工具(含質性與量性)	0	
	課程/模組	0	
	電腦及網路系統或工具	0	
	教材	0	
	舉辦之活動/競賽	0	
	研討會/工作坊	0	
	電子報、網站	0	
	計畫成果推廣之參與（閱聽）人數	0	

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本研究提出利用一種新穎的蜂巢網格標記，作為影像辨識及分析之參考原型，透過該標記所攝得之高速影像資料，再以數位影像相關法計算影格區塊之間相關係數，以分析影格中試體相對位移像素，再搭配次像素分析可進而求得次像素位移，以增加量測精度。在高解析度影像下，於頻率域進行量測資料內含訊息之剖析，與 LVDT 量測之數據比較，可獲得準確的振態頻率，並可藉由 FRF 頻率響應函數識別出結構損壞之位置。本研究之數位影像處理方法可應用於結構健康監測，且此量測系統架設之簡便性亦提供在實際應用的適用性。在現有已發展出來之系統之下，可繼續朝向各種動態影像之識別及分析，以找尋各種不同領域的應用可能性。