行政院國家科學委員會專題研究計畫 成果報告

應用強制振動技術之橋梁顫振導數識別研究
研究成果報告(精簡版)

計 畫 類 別 ：個別型
計 畫 編 號 ：NSC 96-2221-E-032-021-
執 行 期 間 ：96 年 08 月 01 日至 97 年 07 月 31 日
執 行 單 位 ：淡江大學土木工程學系

計 畫 主 持 人：吳重成

計畫參與人員：碩士班研究生-兼任助理人員：顏上為
碩士班研究生-兼任助理人員：王軍翰

報 告 附 件 ：出席國際會議研究心得報告及發表論文

處 理 方 式 ：本計畫可公開查詢

中 華 民 國 97 年 11 月 14 日

行政院國家科學委員會補助專題研究計畫 v 成果報告 □期中進度報告

應用強制振動技術之橋梁顫振導數識別研究

計畫類別： v 個別型計畫　　□整合型計畫
計畫編號： NSC 96-2221-E-032-021
執行期間：　96 年　8 月　1 日至　97　年　7　月　31 日

計畫主持人：吳重成
共同主持人：
計畫參與人員：（研究生）顏上為，王軍瀚

成果報告類型(依經費核定清單規定繳交)：v 精簡報告　□完整報告

本成果報告包括以下應繳交之附件：
□赴國外出差或研習心得報告一份
□赴大陸地區出差或研習心得報告一份
v 出席國際學術會議心得報告及發表之論文各一份
□國際合作研究計畫國外研究報告書一份

處理方式：除產學合作研究計畫、提升產業技術及人才培育研究計畫、列管計畫及下列情形者外，得立即公開查詢
□涉及專利或其他智慧財產權，□一年□二年後可公開查詢

執行單位：淡江大學土木系

中　華　民　國　97　年　11　月　14　日

中文摘要及關鍵詞:

我國近年來經濟高度成長，加快公共建設如高速公路或快速道路等的興建步伐。其中，橋樑常扮演交通運輸上的樞紐，橋樑結構之安全與否，直接間接地對附近地區經濟造成衝擊。橫跨河川的交通運輸橋樑，因聯接距離較長，在力學以及造型美觀的雙重考量下，工程上常採用纜索支撐橋樑設計，加上現今高強度且輕質建材之相繼發明，跨度愈來愈長的橋樑逐漸出現。我國近年來亦逐漸出現跨度較長的纜索支撐橋樑，隨著橋樑跨度的增長，增加了橋樑柔軟度，將使得這些纜索支撐橋樑受風力影響的振動行為愈來愈顯著，在可能發生較大變形之情況下，可能因發散型態之顫振現象出現，在某一臨界風速下，會形成橋樑動態不穩定而崩塌，對於橋樑結構之安全構成相當威脅，1940 年美國之 Tacoma 吊橋在風速二十米左右即發生顫振崩塌之例證可為殷鑑，所以工程上必須對顫振現象有深入的了解。

顫振臨界風速值來自顫振導數(Flutter Derivative)之計算，當風速增加至某一特定值時，自身擾動風力與原結構結合開始出現不穩定，此時之風速即為顫振臨界風速，因此，顫振導數值決定顫振行為。土木橋樑斷面有別於機翼之流線型特性，其形狀多半為鈍體，因此顫振導數無適合之理論式可使用，必須藉由風洞試驗予以識別。傳統自由振動識別法常伴隨兩個主要缺點，其一，由於自由振動之歷時短，試驗者操作之細膩度及風洞周遭天候環境常嚴重影響識別結果；其二，識別出顫振導數之對應頻率為自由振動頻率，並非對應至理論上之外來振動頻率，因此所識別結果與真實值會有差異。

本計畫之研究目標為提出一套全新的氣彈實驗設計與流程，克服傳統自由振動識別法之缺點，提高識別結果之準確度。利用間接強制振動方式驅動斷面模型之振動，藉由反應量測以逆向方式有系統地進行氣彈互制力之識別，可歸類為逆向問題(Inverse Problem)之範疇。工作時程共三年，第一年之主要工作內容為建構強制振動實驗架構，提出識別非耦合項顫振導數之方法與流程，並以流線型平板斷面模型進行實驗驗證。

關鍵詞：橋面版，氣彈互制效應，顫振，顫振導數，強制振動

英文摘要及關鍵詞:

Among many infrastructures, bridge structures are specifically crucial in terms of the development of a country since they in general are responsible for connecting cities culturally and economically. Most of the cross-river bridges, due to their longer span, are considered to be cable-supported style to meet both the esthetical and mechanical needs. In addition, the trend toward using newly developed stronger and lighter material in construction further makes the design of cable-supported bridges with longer span plausible. However, the increased flexibility by the longer span will aggravate the wind effect on bridge structures. The induced vibration becomes large enough to initiate the occurrence of flutter – the most prominent aeroelasticity that can even cause the structural instability under a critical wind speed (flutter speed). A typical example is the collapse of Tacoma Narrows suspension bridge in 1940.

Basically, the flutter speed is obtained from the calculation of the so-called flutter derivatives, which are the essential quantities in the self-excited forces. Because of the bluff body nature of bridge decks in civil infrastructures, the flutter derivatives are best configured by directly performing wind tunnel tests on bridge section models. The methodology of the conventional free vibration approach has been well developed and widely used in many actual practices to date. However, the typical shortcomings out of it include (1) the lack of consistency because of high sensitivity of free vibration responses to test condition and environment, and (2) the discrepancy inherently inherited by treating the free vibration frequency as the excitation frequency.

To overcome these, this project proposes a new approach to identify flutter derivatives using white-noise forced actuation technique, which can be categorized to the scope of inverse problem. A two-axes actuating device, which is composed of two independent electric servo-motors, was used to indirectly drive the motion of the bridge section model through the serial connection of springs. This project is scheduled to be completed in three years. The main task of the 1st year is to develop the identification scheme and technique for determining the uncoupled flutter derivatives, and verify it by performing wind tunnel tests for a chamfered plate section model that simulates thin plate.

Keywords: Bridge Deck, Aero-elasticity, Flutter, Flutter Derivative, Forced Actuation

1. INTRODUCTION

In wind engineering, the importance of bridge aero-elasticity is well recognized because it could potentially cause devastation. A typical example is the collapse of Tacoma Narrows suspension bridge in 1940. It has drawn much attention on researches in the last few decades, among which the most important initiative of modeling such behavior was proposed by [Scanlan *et al.* (1971)] by introducing the idea of flutter derivatives that were originally used in aerospace engineering for predicting the flutter wind speed. Because of the bluff body nature on civil bridge sections, the flutter derivatives are usually determined by performing wind tunnel identification on section models. The methodology of the conventional approach that basically uses free vibration technique has been well developed and widely used in many actual practices. However, the typical shortcomings by this method include (1) the lack of consistancy because free vibration responses are quite sensitive to test condition/environment, and (2) the difficulty of performing time domain analysis for buffeting responses. To overcome these, this paper presents a new approach for identifying uncoupled flutter derivatives using white-noise forced vibration technique.

2. FORMULATION AND EXPERIMENTAL SETUP

2.1 Equation of Bridge Motion Subjected to Smooth Wind Flow and Forced Excitation

Consider a schematic diagram of the experimental setup shown in Fig. 1. The bridge section model is connected to the wind tunnel ceiling and a two-axes actuating device outside the wind tunnel by four springs. Under smooth wind flow and forced excitation, if the section model is restricted to move in either the pitching (torsional) or heaving (vertical) direction individually, the uncoupled equations of motion in both directions can be expressed respectively as

$$J\ddot{\theta}+c_\theta\dot{\theta}+k_\theta\theta=0.5\,c_\theta\dot{\theta}_0+0.5\,k_\theta\theta_0+L_l\,M(t)\,;\quad m\ddot{h}+c_h\dot{h}+k_hh=0.5\,c_h\dot{h}_0+0.5\,k_hh_0+L_l\,L(t) \qquad (1,2)$$

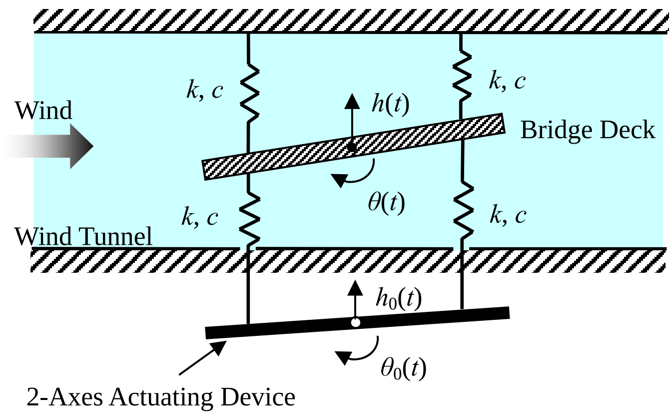

Fig. 1 : Configuration of Experimental Setup

in which m and J are mass and mass moment of inertia w.r.t. the elastic center of the section; h and θ are heaving displacement and pitching angle of the deck; $c_\theta=4cr^2$, $k_\theta=4kr^2$, $c_h=4c$, $k_h=4k$, k and c are spring stiffness and internal damping coefficients, r is spring location to the elastic center of the deck; L_l is section length, $L(t)$ and $M(t)$ are motion-induced lift and moment per unit length; h_0 and θ_0 are heaving displacement and pitching angle generated by the actuating device. For structural identification, the damping ratio and natural frequency of the individual structural system can be identified by complex curve-fitting of frequency response function induced solely by the forced excitation from the actuating device. With the aid of knowing the values of J (or m)

that can be identified by performing linear regression analysis described in [Wu et al. (2005)], the values of c_θ, k_θ, c_h and k_h can be obtained.

2.2 Identification of Uncoupled Flutter Derivatives

Consider the same schematic diagram in Fig. 1. The uncoupled motion-induced $M(t)$ and $L(t)$ per unit length under smooth wind flow can be expressed by [Scanlan *et al.* (1971)]

$$M(t) = \rho U^2 B^2 \,[K\, A_2^* B\, \dot{\theta}(t)/U + K^2 A_3^* \theta(t)] \;\; ; \;\; L(t) = \rho U^2 B\,[K\, H_1^*\, \dot{h}(t)/U + K^2 H_4^* h(t)/B] \qquad (3, 4)$$

in which ρ is air density; U is mean wind velocity; B is bridge width, K is non-dimensional frequency defined as $K = D\omega/U$; ω is excitation frequency in rad/sec; A_2^*, A_3^*, H_1^* and H_4^* are uncoupled flutter derivatives. Taking Fourier transform on Eqs. (3) and (4) leads to

$$\overline{M}(iK) = H_{M/\theta}(iK)\cdot\overline{\theta} \;\; ; \;\; H_{M/\theta}(iK) = \rho U^2 B^2\,[i\, A_2^* + A_3^*]\, K^2 \qquad (5)$$

$$\overline{L}(iK) = H_{L/h}(iK)\cdot\overline{h} \;\; ; \;\; H_{L/h}(iK) = \rho U^2\,[i\, H_1^* + H_4^*]\, K^2 \qquad (6)$$

in which the bar represents values in the frequency domain. Due to page limitation, in what follows, only the formulation for the motion in the pitching direction will be presented, while those in the heaving direction can be derived in the same manner. It can be assumed that $H_{M/\theta}(iK)$ can be realized by an equivalent linear system that has a frequency response function

$$H_{M/\theta}(iK) = \rho U^2 B^2 [\overline{b}_n (iK)^n + \overline{b}_{n-1}(iK)^{n-1} + \cdots + \overline{b}_0]/[(iK)^m + \overline{a}_{m-1}(iK)^{m-1} + \cdots + \overline{a}_0] \qquad (7)$$

In Eq. (7), the order of the numerator should be larger than that of the denominator ($n>m$) and $\overline{a}_i$, $\overline{b}_i$ are constant coefficients that are to be identified through the following procedures. Once $\overline{a}_i$, $\overline{b}_i$ are determined, the flutter derivatives A_2^*, A_3^* can be computed by considering the imaginary and real parts accordingly. Alternatively, Eq. (7) can be written in $(i\omega)$ as

$$H_{M/\theta}(i\omega) = [b_n (i\omega)^n + b_{n-1}(i\omega)^{n-1} + \cdots + b_0]/[(i\omega)^m + a_{m-1}(i\omega)^{m-1} + \cdots + a_0] \qquad (8)$$

by converting the coefficients following the relations

$$a_j = \bar{a}_j (B/U)^{j-m} \, (j = 0,1,\cdots,m-1) \; ; \quad b_j = \rho U^2 B^2 \, \bar{b}_j (B/U)^{j-m} \, (j = 0,1,\cdots,n) \tag{9}$$

or further rewritten in terms of the quotient and residue as

$$H_{M/\theta}(i\omega) = \sum_{j=0}^{l} Q_j \, (i\omega)^j + [c_{m-1}(i\omega)^{m-1} + \cdots + c_0]/[(i\omega)^m + a_{m-1}(i\omega)^{m-1} + \cdots + a_0] \; ; \quad l = n-m \tag{10}$$

Therefore, according to the theorem in linear system, the time-domain realization can be obtained by a state space representation expressed by

$$\dot{\mathbf{Z}} = \mathbf{A}_\theta \mathbf{Z} + \mathbf{B}_\theta \, \theta \; ; \quad M = \mathbf{C}_\theta \mathbf{Z} + \sum_{j=0}^{l} Q_j \, \theta^j \tag{11}$$

From the physical point of view, it is conceivable to assume $l = n - m = 1$ for simplicity. The substitution of Eq. (11) into Eq. (1) yields

$$J\,\ddot{\theta} + c_\theta \, \dot{\theta} + k_\theta \, \theta = 0.5\, c_\theta \, \dot{\theta}_0 + 0.5 k_\theta \, \theta_0 + L_l \cdot (\mathbf{C}_\theta \mathbf{Z} + Q_0 \, \theta + Q_1 \, \dot{\theta}) \tag{12}$$

With Eq. (12) further cast with Eq. (11), the overall state equation incorporating aero-elasticity can be finally formed and expressed as

$$\begin{aligned} \dot{\mathbf{q}} &= \mathbf{A}\,\mathbf{q} + \mathbf{B}\,\theta_0 \\ \theta &= \mathbf{C}\,\mathbf{q} \end{aligned} \tag{13}$$

in which

$$\mathbf{q} = \begin{bmatrix} \theta \\ \dot{\theta} \\ \mathbf{Z} \end{bmatrix} ; \quad \mathbf{A} = \begin{bmatrix} 0 & 1 & \mathbf{0} \\ -J^{-1}(k_\theta - L_l Q_0) & -J^{-1}(c_\theta - L_l Q_1) & J^{-1} L_l \mathbf{C}_\theta \\ \mathbf{B}_\theta & \mathbf{0} & \mathbf{A}_\theta \end{bmatrix} ; \quad \mathbf{B} = \begin{bmatrix} 0 \\ J^{-1} \\ \mathbf{0} \end{bmatrix} ; \quad \mathbf{C} = [\; 0.5 k_\theta \quad 0.5 c_\theta \quad \mathbf{0} \;] \tag{14}$$

Therefore, with aero-elasticity incorporated, the frequency response function θ induced by θ_0 can be given by

$$H_{\theta/\theta_0}(i\omega) = \mathbf{C}\left((i\omega)\mathbf{I} - \mathbf{A}\right)^{-1} \mathbf{B} \tag{15}$$

Under wind flow, by measuring the frequency response function induced by actuation, the coefficients in $\mathbf{A}_\theta$, $\mathbf{C}_\theta$, and Q_0 and Q_1 can be determined properly by minimizing a performance index consisting of the sum of square error between the experimental data and the theoretical value by Eq. (15) under various wind speeds, i.e., $PI = \sum_{U=U_1}^{U_n} \sum_{k=1}^{N} w_k^U \,|\, H_{\theta\theta_0}^U(i\omega_k) - f_k^U \,|^2$, which is constrained by the conditions of $\mathbf{A}_\theta$ and $\mathbf{A}$ being stable, i.e., $\mathrm{Re}\lambda(\mathbf{A}_\theta) < 0$; $\mathrm{Re}\lambda(\mathbf{A}) < 0$.

In PI, f_k^U represents the k-th experimental frequency response; w_k^U is weighting assigned for the k-th point under wind velocity U. To ensure that global minimization can be achieved, the genetic algorithm (GA) [Man, Tang and Kwong (1999)] and conventional gradient method were used in cooperation for searching the optimal solution.

3. EXPERIMENTAL RESULTS

For demonstration, the bridge deck of a chamfered plate with a width/depth ratio of 25, as shown in Fig. 2, was placed in a wind tunnel to conduct the identification. Wind tunnel tests at 6 different wind velocities with white-noise actuation activated were performed for the pitching motion, while 5 wind velocities were used for the heaving motion. The resulting frequency response functions are plotted in Fig. 3 (a) and (b), respectively. Following the approach presented, the identified flutter derivatives A_2^*, A_3^*, H_1^* and H_4^* versus the reduced wind speed $\hat{U}$ ($\hat{U} = U/fB$; f is the excitation frequency) are shown in Fig. 4 (a)-(d), respectively, in which the flutter derivatives from Theodorsen functions are also plotted for comparison. Time history analysis was also simulated for verification and the comparison with the experimental data shows excellent correlation. However, these figures are not shown due to page limitation.

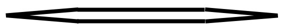

Fig. 2: Bridge Deck Section

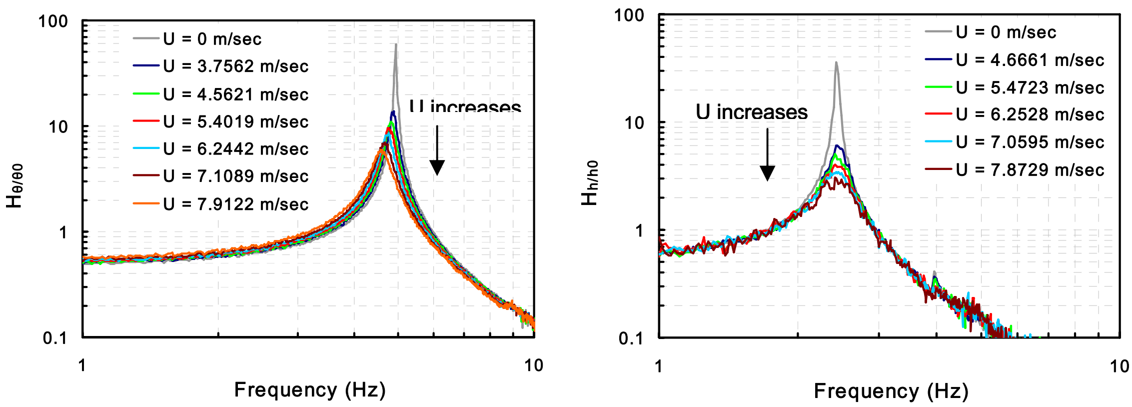

Fig. 3: (a) Frequency Response Function in Pitching Motion; (b) Frequency Response Function in Heaving Motion

4. CONCLUDING REMARKS

This research presents a new approach to identify the uncoupled flutter derivatives of bridge decks by using white-noise forced vibration to overcome the shortcomings in the conventional approach. A bridge deck composed of a chamfered plate with a width/depth ratio of 25 has been used to successfully demonstrate the applicability of this approach. This approach also provides a direct link between flutter derivatives and state space equations, which can facilitate the time domain analysis for buffeting responses of bridges, that is, employing Eq. (13) and (14) with θ_0 replaced by the external buffeting moment.

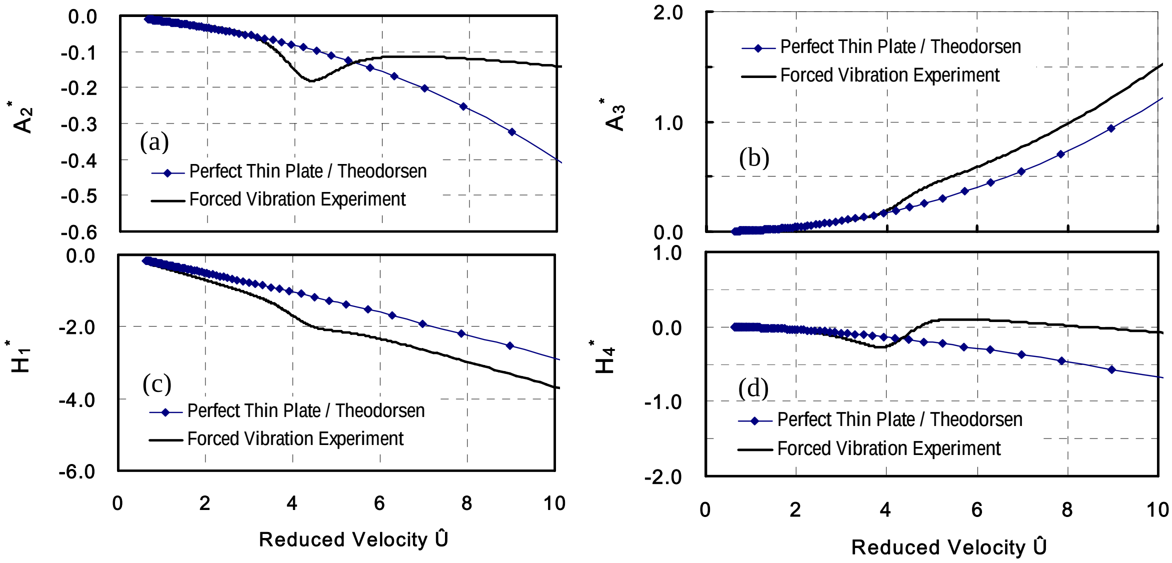

Fig. 4: Comparisons of Identified Flutter Derivatives with Those from Theodorsen Functions

5. REFERENCES

1 J. C. Wu and S. W. Lin, Identification of Aero-elasticity of High-rise Buildings Using Forced Excitation, Proc. 6th *Asia-Pacific* Conf. on Wind Engineering, Seoul, Korea, 2005.

2 Man, Tang and Kwong, Genetic Algorithm, Springer, 1999.

3 R. H. Scanlan and J. J. Tomko, Airfoil and Bridge Deck Flutter Derivatives, J. Eng. Mech. Div., 1971.

出席國際學術會議心得報告

計畫編號	NSC 96-2221-E-032-021
計畫名稱	應用強制振動技術之橋梁顫振導數識別研究
出國人員姓名 服務機關及職稱	吳重成 淡江大學 土木工程系 教授
會議時間地點	97年5月29-31日 韓國濟州(Jeju)
會議名稱	第4屆國際風與結構研討會 The 4th International Conference on Advances in Wind and Structures (AWAS '08)
發表論文題目	Tentative Results on Wind-Induced Comfort Threshold Based on A Newly Constructed Motion Simulator

一、參加會議經過

本屆國際風與結構研討會於五月二十九日至三十一日在韓國濟州(Jeju)之Seowipo KAL Hotel的會議中心舉行。此次會議由Korea Advanced Institute of Science and Technology (KAIST)主辦，協辦單位包括Wind Engineering Institute of Korea及Korea Institute of Construction Technology。會議籌備委員會主席為Chang-Koon Choi博士（韓國）與John D. Holmes (紐西蘭)，另由各國學者三十餘人組成委員會籌理各項會務。

本會議宗旨在研討風與結構相關主題之最新理論與應用技術，為KAIST主辦四年一次之例行學術活動，今年為第四屆，本會議為風工程領域中重要會議，共有來自世界二十餘國共發表160篇學術論文。

五月二十九日上午參加開幕式，接著聆聽紐西蘭J. Holmes教授之Keynote Lecture「Windborne Debris and Damage Risk Models : a Review」及加拿大RWDI公司Jiming Xie博士之Invited Lecture「Progress of Wind Tunnel Techniques in Practical Application」。前者講述到風引起殘骸碎片之損害理論模型，其中大部分為近年發展之回顧，後者則闡述風洞技術於實際應用之發展狀況。茶歇後並參與多個平行議程其它論文之聽講與討論。晚上於飯店陽台參加迎賓接待(Reception)晚餐，與來自各國之與會學者寒敘並交換研究心得，盡興而歸。

五月三十日上午參加M. Matsumoto(日本)教授之Keynote Lecture「Mechanism of How to Suppress Wind-Induced Vibration of Inclined Cable of Cable-Stayed Bridges」，講述纜繩受風之力學行為，包括有雨及無雨之情況，大部分為作者在此主題上之畢生研究大略概述。之後並聆聽K. C. S. Kwok (香港)教授之Invited Lecture 「Occupant Comfort Test

Using a Tall Building Motion Simulator」，因該主題與本人與會論文強烈相關，因此藉機提問有關舒適度標準對應之迴歸期問題。從獲得之回答推估，迴歸期問題為目前學界尚未有系統進行定量研究之主題，未來應有發揮空間。茶歇後並參與多個平行議程其它論文之聽講與討論。下午Session 5A (13:55~15:10)第一場為筆者參與論文「Tentative Results on Wind-Induced Comfort Threshold Based on A Newly Constructed Motion Simulator」的發表，同時筆者也應邀擔任該場之主持工作。本論文為近年風洞投入相當物力及人力之研究，從振動模擬台之設計施工，到完工後測試並開始建構舒適度試驗室，以進行振動舒適度測試及相關問卷調查，歷時兩年有餘。目前完成理論架構之建模並套入初步測試問卷調查結果，整理發表於此篇論文。會後並回答數個與會學者之提問，同時對於迴歸期問題有更進一步之討論。晚上在該飯店舉行大會晚宴，與會場各國代表餐敘交流，賓主盡歡。

五月三十一日上午參加Young-Duk Kim (韓國)教授之Keynote Lecture「Experimental and Numerical Study on Wind-Induced Noise of Thin Columns」，及S. D. Kwon (韓國)教授之「Aerodynamic Design of Long-Span Bridges in Korea」。茶歇後並參與平行議程其它論文之聽講與討論，於11:30大會圓滿結束。

二、與會心得

本次會議淡江大學風工程研究中心共 2 人參加，發表兩篇論文為多年來與其他三位教師研究整合之成果，會中吾等的研究能量與成果獲得肯定，並有機會與從事相關研究的學者深入交換意見，多方收集資料以為未來擬定研究方向之參考。

會中結交多位日本、中國大陸、韓國與美國學者，希望能擴大接觸層面，增加學術交流之機會，同時為1年後本校主辦之亞太風工程會議廣為宣傳，初步了解反應熱烈，對到台灣參加會議充滿了期待。

三、建議

此行參加會議收獲豐碩，交換研究訊息，對以後研究將有立即與實質上的助益。在此特別表達對國科會此行補助的感謝之意，並希望持續此一政策，鼓勵學者參與國際性學術活動，充實研究內容，擴展國際視野，以提升本中心之學術聲望和影響力。

四、攜回資料名稱及內容:

議程表、會議摘要論文集一冊及論文光碟片一片。

Tentative Results on Wind-Induced Comfort Threshold Based on A Newly Constructed Motion Simulator

* Jong-Cheng Wu [1)], Chii-Ming Cheng [2)] and Jeng-Tang Chen[3)]

[1)] *Department of Civil Engineering, Tamkang University, Taipei, Taiwan, Tel: 886-2-26215656 ext.2758, Fax: 886-2-26209747, Email: joncheng@mail.tku.edu.tw.*
[2)] *Department of Civil Engineering, Tamkang University, Taipei, Taiwan.*
[3)] *Department of Civil Engineering, Tamkang University, Taipei, Taiwan.*

ABSTRACT

Under wind disturbance, the comfort of occupants in buildings is an important issue in the structural design aside from safety consideration. The human comfort criterion for wind-induced motion has been a long-time controversial issue because many factors, either physiological or psychological, can considerably differentiate the outcome. Recently, a constant criterion of 5 cm/sec^2 for a half-year return period was regulated in Taiwan building wind code. In an attempt to build up the local data base in preparation for improving the building wind code in the future, a research project was initiated, aiming to conduct surveys to investigate the comfort criteria by using a motion simulator newly constructed at the wind engineering research center, Tamkang University. In this paper, a preliminary study emphasizing on constructing the methodology and feasible procedure to determine the comfort threshold and the return period is conducted for the continuous researches in the long run. The tentative results following the procedure are presented, however, a definitive conclusion is not as yet reached until sufficient samples can be collected in the future.

INTRODUCTION

Aside from safety consideration, the comfort of occupants in buildings due to wind disturbance is an important issue in the structural design. Especially for high-rise buildings in which the excessive wind-induced motion occurs so frequently, the need of resolution to alleviate the discomfort of occupants may dominate the structural design. It is well recognized

---

[1)] Professor
[2)] Professor
[3)] Graduate Student

that the acceleration is the representative quantity that directly reflects on the motion perception and comfort. The human perception for wind-induced motion has been a long-time controversial issue. The perception of motion is physiologically determined by the vestibular system in the inner ear, however, psychological effect may play a crucial role as well. Other related factors such as body posture, body orientation, motion waveform, task distraction, gender, age, visual cue, auditory cue and others, according to earlier research literature, can considerably differentiate the outcome. In these previously conducted researches, some were based on the people survey in actual buildings [Hansen *et al*. (1973), Goto (1983), Jeary *et al*. (1988), Isyumov and Kilpatrick (1996), Denoon et al. (1999), *etc*.], some used survey data from a motion simulator [Khan and Parmelee (1971), Chen and Robertson (1972), Shioya and Kanda (1993), Burton et al. (2006), Kwok et al. (2007), *etc*.]. Because of the complexity of human senses on motion perception and comfort, and the influence of different test conditions, some papers gave distinctive results while some showed good agreement. Interestingly, some recent researches have even shown strong evidence to confirm on the frequency dependency of the motion perception and comfort threshold [Denoon et al. (1999), Burton et al. (2006), Kwok et al. (2007)].

From the engineer's perspective, it is the comfort criteria which is related to structural design, rather than the motion perception criteria, because the message that structures could move under disturbance is supposed to be conveyed to the general public education. For people living in earthquake and typhoon prone region, this understanding is not difficult for them, especially adults, because of the personal experience in the past. It is obvious that people require higher level of motion to feel the discomfort.

In authors' opinion, even under the same test condition, there are two basic issues that need to be addressed before further consensus can be approved. If the comfort threshold is considered as a random variable in the analysis of statistical survey data, the definition of cumulative percentage to which the comfort threshold corresponds should be clarified first. In the previous literature, its variation ranges from 2 percentile [Hansen *et al*. (1973), Kwok et al. (2007), Burton et al. (2006)], 10, 50 (median) to 90 percentile [Chen and Robertson (1972), Jeary, *et al*. (1988)]. Secondly, it is also observed that very few articles discussed the methodology of determining the return period for the comfort threshold [Hansen *et al*. (1973), Goto (1983)]. The return period, herein means the recurrence period of a given motion that people feel intolerable. In fact, return period is critically important because it is to be specified on the mean wind speed for analyzing the structural acceleration in checking the satisfaction of comfort.

Despite of the difficulty in finding agreement, there is an imminent need for practitioners to have a comfort guideline for design purpose. To date, ISO 6897-1984 [International Organization for Standardization (1984)] and Japan building wind code [Architectural Institute of Japan (2004)] have officially stated the criteria for human comfort. The ISO 6897-1984 basically adopted the suggestion in Irwin (1978, 1986) as the comfort criterion, which is defined as "not more than 2% of occupants give adverse comments about the motion with a return period of 5 years or more". The criteria stated in Japan building wind code, however, is based on the combined consideration of the criteria proposed in Goto (1975, 1983), Kanda *et al*. (1988) and ISO 6897-1984, with the return period set to one year. In addition, Australia building wind code [Standards Australia/ Standards New Zealand (2002)] referred to the articles of Melbourne and Cheung (1988) and Melbourne (1998) for the comfort issue, which are essentially the same as regulated in ISO 6897-1984 except using peak acceleration instead. Tentatively, ASCE the

Council of Tall Buildings and Urban Habitat technical committee also suggested the criteria proposed in Isyumov (1993) as the guideline.

In Taiwan building wind code [Architecture and Building Research Institute of Taiwan (2007)], a constant criterion of 5 cm/sec^2 for a half-year return period was recently regulated. Apparently, considerable debates continue in two reasons. One is the frequency independence of the criterion, and the second is the choice of a half-year for the return period. In an attempt to build up the local data base in preparation for improving Taiwan building wind code in the future, a research project was initiated, aiming to conduct surveys to investigate the comfort criteria by using a motion simulator newly constructed at the wind engineering research center, Tamkang University. In this paper, a preliminary study emphasizing on constructing the methodology and feasible procedure to determine the comfort threshold and the return period is conducted for the continuous researches in the long run. The tentative results following the procedure are presented, however, a definitive conclusion is not as yet reached until sufficient samples can be collected in the future.

EXPERIMENTAL SETUP

1. Motion Simulator

The motion simulator consists of a 1.5mx 1.5m platform driven by two independent AC servo-motors in x and y directions (planar motion), respectively, through two sets of high-precision ball screws and linear guideways, as shown in Fig. 1. The servo-motors are controlled by a motion control card through the command of a personal computer. A coded program written in Visual Basic is used to interface between the user and the motion control card in the mode of pulse control. The simulator has a maximum stroke of 600 mm and maximum payload of one metric ton. In each direction, it is capable of producing a harmonic motion with a maximum acceleration of 0.5g within the frequency range of 0~3 Hz, with the stroke not exceeding its maximum. For random motion, the frequency range is expected to be higher. Thus, the maximum acceleration for harmonic motion is 23.7 cm/sec^2 (24.2 milli-g) at 0.1 Hz and 491 cm/sec^2 (500 milli-g) at 1 Hz, which are enough to cover the range for comfort tests of wind-induced motion.

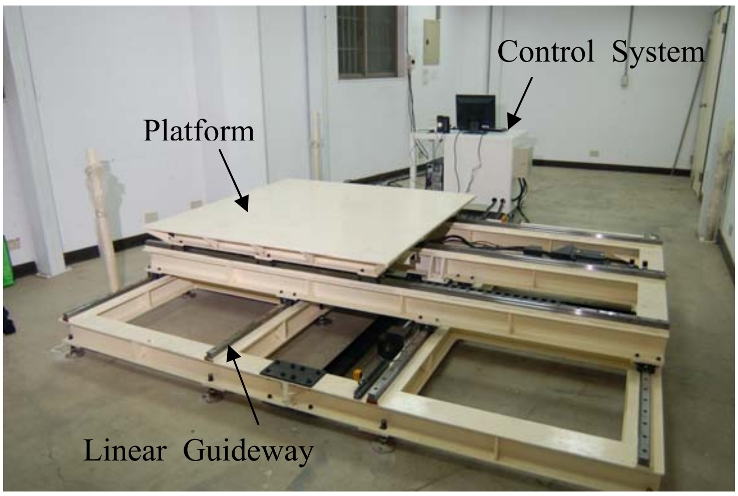

Fig. 1: Completed 2-Axes Motion Simulator

2. Test Chamber:

A test chamber with a dimension of 2 m (Length) by 3 m (Width) by 1.9 m (Height), which is decorated as a study room or living room, was constructed directly on the top of the platform as shown in Fig. 2 (a). The structure of the chamber is designed to be stiff enough to avoid vibration from itself during the motion of the simulator. The space of the test chamber, as shown in Fig. 2 (b), can accommodate two test subjects to attend the test simultaneously. The chamber is also installed with a window which can be open or closed by blinds, depending on if the visual effect is to be taken into account in the test. Shown in Fig. 3 is a perspective view of the overall arrangement of the 2-axes motion simulator, test chamber and other facilities in the laboratory.

Fig. 2: Pictures of the Test Chamber: (a) Outside View; (b) Inside View

Fig. 3: A Perspective View of the Arrangement of the 2-Axes Motion Simulator, Test Chamber and Other Facilities in the Laboratory

DESIGN AND PROCEDURE OF COMFORT TESTS

Comfort threshold, by the definition in ISO 6897, means the situation when people give adverse comment on the motion. Therefore, the caused discomfort due to motion could be physical, psychological, task disruption or interaction of them. The physical symptom of motion sickness includes dizziness, nausea or headache, and the psychological symptom can be mainly interpreted as "uneasiness and strain". The task disruption means "inability to a certain type of activity and/or work".

Table 1: Ranges of Amplitudes and Frequencies in Comfort Tests

	0.1 Hz		0.2 Hz		0.4 Hz		0.6 Hz		0.8 Hz		1.0 Hz	
	D (mm)	*A* (mm/ s^2)	*D* (mm)	*A* (mm/ s^2)	*D* (mm)	*A* (mm/ s^2)	*D* (mm)	*A* (mm/ s^2)	*D* (mm)	*A* (mm/ s^2)	*D* (mm)	*A* (mm/ s^2)
Level 1	250	99	40	63	5	32	4	57	1.2	30	0.8	31
Level 2	300	118	50	79	10	63	5	71	1.5	38	1.1	43
Level 3	350	138	60	95	15	95	6	85	2	50	1.2	47
Level 4	400	158	70	110	20	126	7	99	2.5	63	1.3	51
Level 5	450	177	80	126	25	158	8	114	3	76	1.4	55
Level 6	500	197	110	174	30	189	9	128	3.5	88	1.6	63
Level 7	550	217	150	237	35	221	12	170	4	100	2	79
Level 8	600	237	200	316	40	252	15	213	5	126	2.6	102

Table 2: Percentage of Test Subjects Giving Adverse Comments

	0.1 Hz		0.2 Hz		0.4 Hz		0.6 Hz		0.8 Hz		1.0 Hz	
	A (mm /s^2)	%	*A* (mm /s^2)	%	*A* (mm /s^2)	%	*A* (mm /s^2)	%	*A* (mm /s^2)	%	*A* (mm /s^2)	%
Level 1	99	0.0	63	0.0	32	3.6	57	8.0	30	3.6	31	3.8
Level 2	118	0.0	79	0.0	63	3.6	71	8.0	38	3.6	43	3.8
Level 3	138	3.8	95	7.1	95	17.9	85	12.0	50	7.1	47	7.7
Level 4	158	3.8	110	10.7	126	17.9	99	12.0	63	14.3	51	7.7
Level 5	177	11.5	126	17.9	158	21.4	114	16.0	76	17.9	55	11.5
Level 6	197	11.5	174	21.4	189	35.7	128	16.0	88	25.0	63	11.5
Level 7	217	19.2	237	50.0	221	39.3	170	28.0	100	32.1	79	15.4
Level 8	237	19.2	316	64.3	252	46.4	213	32.0	126	35.7	102	23.1
λ	5.888		5.518		5.649		5.913		5.102		5.419	
ς	0.526		0.617		0.949		1.193		0.876		1.064	

Twenty-eight graduate students consisting of twenty-three males and five females, aged from 22 to 26, were invited as the test subjects for carrying out a series of tests with various amplitudes and frequencies in uni-direction. The test series cover the frequencies ranged from 0.1 to 1.0 Hz, combined with different amplitudes as tabulated in Table 1. In this preliminary study, only no visual cue was imposed on the test condition, other factors, such as posture (standing or sitting), task distraction (reading, writing, or watching movies) and body orientation (fore-apt or side-to-side directions) were not particularly specified as the first round trial. That is, the subjects were free to take the test based on their personal choice, however, those data will be still recorded as references. More parametric studies based on a specific test condition will be performed sequentially in the near future.

Each test lasts for thirty minutes. Upon completion of each test immediately follows a questionnaire survey to record his/her perception on motion and discomfort as well. The test subject needs to answer if he/she perceives a motion, and the reason why he/she has such a feeling. In case that the test subject gives adverse comments, he/she will be also asked an opinion about the longest intolerable recurrence period on that event. For statistical analysis, the longest intolerable recurrence period in the questionnaire is divided into five categories: 1 month, 2~3 months, 4~6 months, 1 year and 2~3 years, which is a multiple choice. The perception levels for motion and discomfort can be thus recorded and distinguished, while the concern in our research is mostly placed on the comfort criteria.

ANALYSIS OF COMFORT THRESHOLD

Since the acceleration amplitude in a motion is a quantity that directly reflects on the motion perception, it will be used to quantify the comfort threshold in the analysis. However, for harmonic motion with long duration, the comfort threshold is better represented by using the acceleration root-mean-square (RMS) value later as was used in ISO 6897-1984.

Due to the random nature of survey data, the distribution of comfort threshold can be statistically analyzed. It is reasonable to assume the comfort threshold under the same frequency is a random variable that follows the probability density function (PDF) of a lognormal distribution expressed as [Chen and Robertson (1972), Shioya and Kanda (1993)]

$$f_X(x) = \frac{1}{\sqrt{2\pi}\,\varsigma\,x}\exp\left[-\frac{1}{2}\left(\frac{\ln x - \lambda}{\varsigma}\right)^2\right] \tag{1}$$

in which the random variable X represents the comfort threshold; x is an acceleration amplitude; λ is the mean value of ln X; ς is the standard deviation of ln X. Therefore, in the survey data, the percentage of test subjects giving adverse comments is corresponding to the cumulative distribution function (CDF) of X equal to

$$P(X < a) = \int_{-\infty}^{a} f_X(x)\ dx \tag{2}$$

in which a is the given acceleration amplitude. The percentage of test subjects giving adverse comments from our survey data is listed in Table 2 for each frequency. These data will be best fit into the CDF in Eq. (2) by using numerical minimization technique from which the two parameters λ and ς can be determined. The resulting values of λ and ς in each frequency case are listed in Table 2, while the curve-fitted CDFs of the percentage of test subjects giving adverse comments for each frequency case are shown in Fig. 4.

As adopted in ISO 6897, herein the comfort threshold is set at where 2% of the test subjects give adverse comments. Hence, in each frequency case, the assignment of $P(X < a)$ equal to 2% leads to the value of comfort threshold. Their values in terms of acceleration amplitudes and RMS are tabulated in the 2nd and 3rd columns of Table 3.

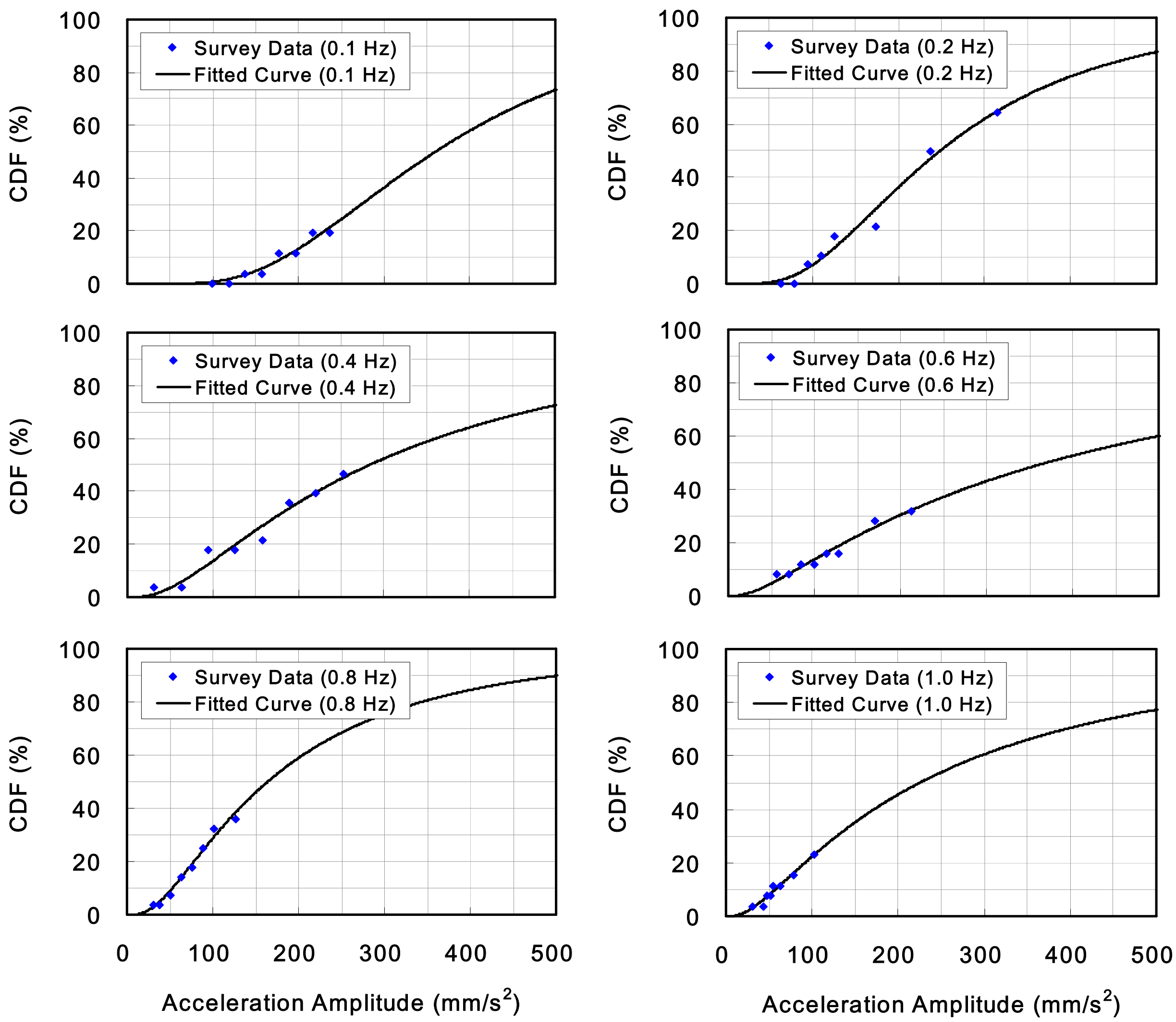

Fig. 4: Curve-Fitted Cumulative Distribution Functions of the Percentages of Test Subjects Giving Adverse Comments for Various Frequencies

Table 3: Tentative Comfort Thresholds and Return Periods for Various Frequencies

Frequency (Hz)	Comfort Threshold		Return Period *R* (Year)
	Acceleration Amplitude *A* (mm/sec^2)	Acceleration RMS (milli-g)	
0.1	122	8.8	0.39
0.2	70	5.1	0.34
0.4	40	2.9	0.48
0.6	32	2.3	1.27
0.8	27	1.9	1.04
1.0	25	1.8	0.95

ANALYSIS OF RETURN PERIOD

The analysis of the return period is based on the survey data of intolerable recurrence period. In the survey data, the five categories of the longest intolerable recurrence period: “1 month”, “2~3 months”, “4~6 months”, “1 year”, and “2~3 years” are corresponding to five categories in terms of the lowest intolerable recurrence rate: “4~6 times in a year”, “2~3 times in a year”, “less than once in a year”, and “once in a year”, respectively.

By assuming that the probability of a given motion occurring in a year follows the Poisson process, the probability of such an event occurring *i* times in a year can be expressed as

$$p(i) = \frac{\nu^i e^{-\nu}}{i!} \quad (3)$$

where ν is the mean occurrence rate in a year, which is related to the return period *R* by *R*=1/ν. Furthermore, by assuming that the percentage of people objecting is a random variable, the expected percentage of people objecting can be calculated by the formula expressed as [Hansen *et al*. (1973)]

$$\mathrm{E}[P] = P_{\le 1} \cdot p(1) + P_{2-3} \cdot \sum_{i=2}^{3} p(i) + P_{4-6} \cdot \sum_{i=4}^{6} p(i) + P_{7-12} \cdot \sum_{i=7}^{12} p(i) \quad (4)$$

Table 4: Percentage of People Objecting Occurrence Rate

	0.1 Hz				0.2 Hz				0.4 Hz			
	$P_{\le 1}$ (%)	P_{2-3} (%)	P_{4-6} (%)	P_{7-12} (%)	$P_{\le 1}$ (%)	P_{2-3} (%)	P_{4-6} (%)	P_{7-12} (%)	$P_{\le 1}$ (%)	P_{2-3} (%)	P_{4-6} (%)	P_{7-12} (%)
Level 1	0	0	0	0	0	0	0	0	0	3.57	3.57	3.57
Level 2	0	0	0	0	0	0	0	0	0	3.57	3.57	3.57
Level 3	0	4	4	4	0	0	7.14	7.14	3.57	3.57	17.9	17.9
Level 4	0	4	4	4	0	0	10.7	10.7	3.57	3.57	17.9	17.9
Level 5	0	4	12	12	0	7.14	17.9	17.9	3.57	10.7	21.4	21.4
Level 6	0	4	12	12	3.57	14.3	21.4	21.4	14.3	21.4	35.7	35.7
Level 7	4	16	20	20	14.3	32.1	50.0	50.0	17.9	25.0	39.3	39.3
Level 8	8	16	20	20	25.0	46.4	64.3	64.3	21.4	32.1	46.4	46.4
	0.6 Hz				0.8 Hz				1.0 Hz			
	$P_{\le 1}$ (%)	P_{2-3} (%)	P_{4-6} (%)	P_{7-12} (%)	$P_{\le 1}$ (%)	P_{2-3} (%)	P_{4-6} (%)	P_{7-12} (%)	$P_{\le 1}$ (%)	P_{2-3} (%)	P_{4-6} (%)	P_{7-12} (%)
Level 1	3.85	3.85	7.69	7.69	3.57	3.57	3.57	3.57	3.85	3.85	3.85	3.85
Level 2	3.85	3.85	7.69	7.69	3.57	3.57	3.57	3.57	3.85	3.85	3.85	3.85
Level 3	7.69	11.5	11.5	11.5	3.57	7.14	7.14	7.14	3.85	3.85	7.69	7.69
Level 4	7.69	11.5	11.5	11.5	3.57	7.14	14.3	14.3	3.85	3.85	7.69	7.69
Level 5	7.69	11.5	15.4	15.4	3.57	10.7	17.9	17.9	3.85	3.85	11.5	11.5
Level 6	3.85	11.5	15.4	15.4	3.57	7.14	25.0	25.0	3.85	7.69	11.5	11.5
Level 7	11.5	15.4	26.9	26.9	7.14	14.3	32.1	32.1	3.85	7.69	15.4	15.4
Level 8	15.4	19.2	30.8	30.8	10.7	25.0	35.7	35.7	7.69	19.2	23.1	23.1

in which P_i is a statistical data from the survey, representing the percentage of people objecting i times occurrence of such an event. For instance, $P_{\le 1}$ is the percentage of people recorded in the categories "less than once in a year" and "once in a year", P_{2-3} is the sum of percentage of people recorded in the category "2~3 times in a year" and $P_{\le 1}$, P_{4-6} is the sum of percentage of people recorded in the category "4~6 times in a year" and P_{2-3}, and so forth.

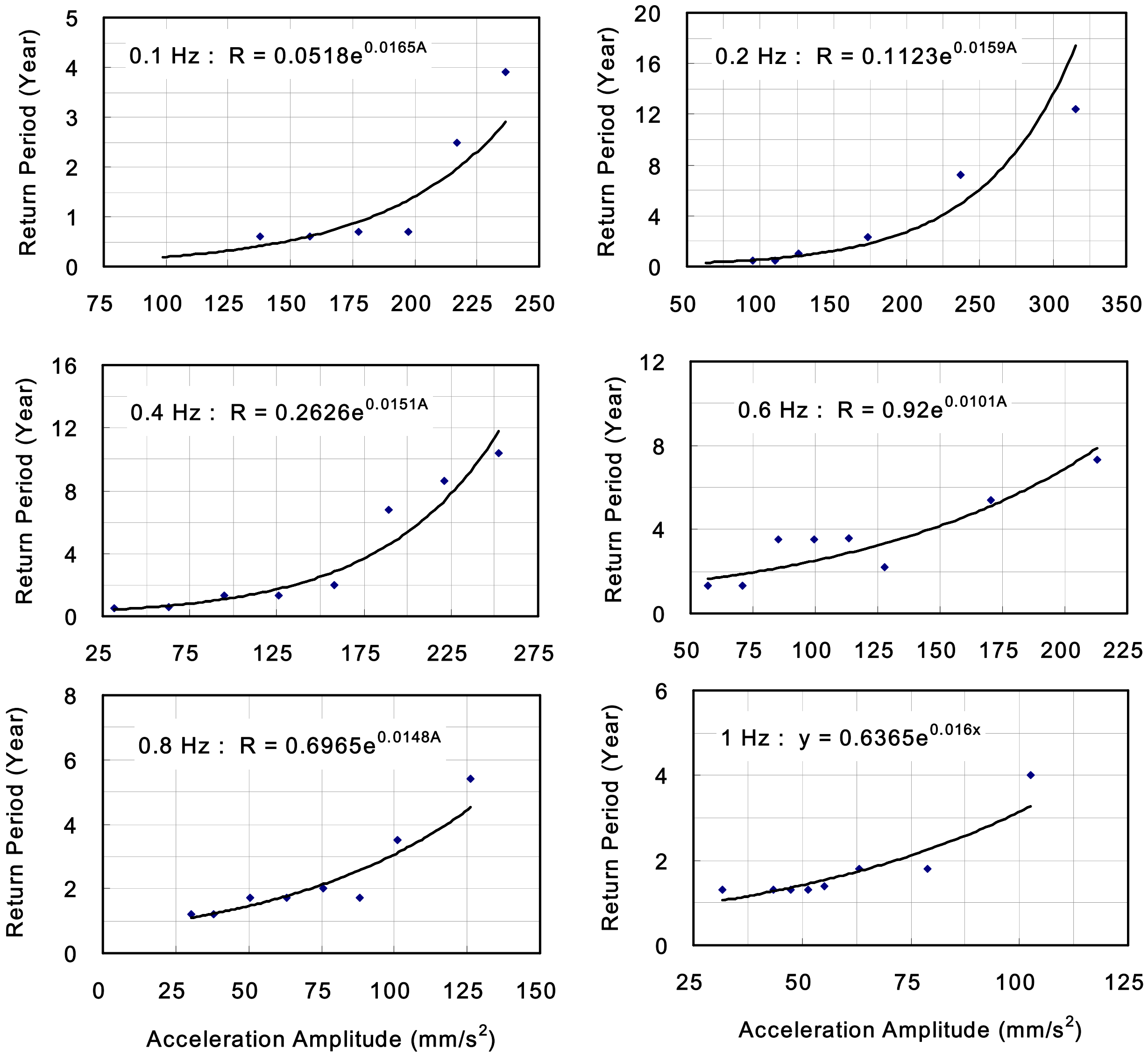

Fig. 5 : Return Period versus Acceleration Amplitude for Various Frequencies

Shown in Table 4 are those recorded values of percentage of people objecting occurrence in each event. As observed from Eq. (4), it depicts the relation between the return period and the expected percentage of people objecting. Since the comfort threshold is set at where 2% of the people give adverse comments, the return period corresponding to 2% expected percentage of people objecting is to be determined for each event. Then, for each frequency, such return periods thus determined versus the acceleration amplitudes can be curve-fitted in an exponential function, as shown in Fig. 5. Thus, the return period corresponding to the comfort threshold can be obtained by interpolating or extrapolating the curves in Fig. 5. The tentative results of the return periods for comfort thresholds are shown in the last column of Table 3. Although the values seem to be quite close to one year, they are not yet conclusive at this moment.

COMPARISON WITH ISO 6897-1984

The tentative results of comfort threshold in terms of acceleration RMS are plotted in Fig. 6 for comparison with ISO 6897. Two solid curves in Fig. 6 are the thresholds proposed by ISO 6897, one is the original curve for return period equal to 5 years, another one is the curve for return period equal to 1 year by multiplying 0.72 as suggested in ISO 6897. The comparison at the moment is to see the general trend, more conclusive remark will not be made until more data collection from continuing survey are completed in the future.

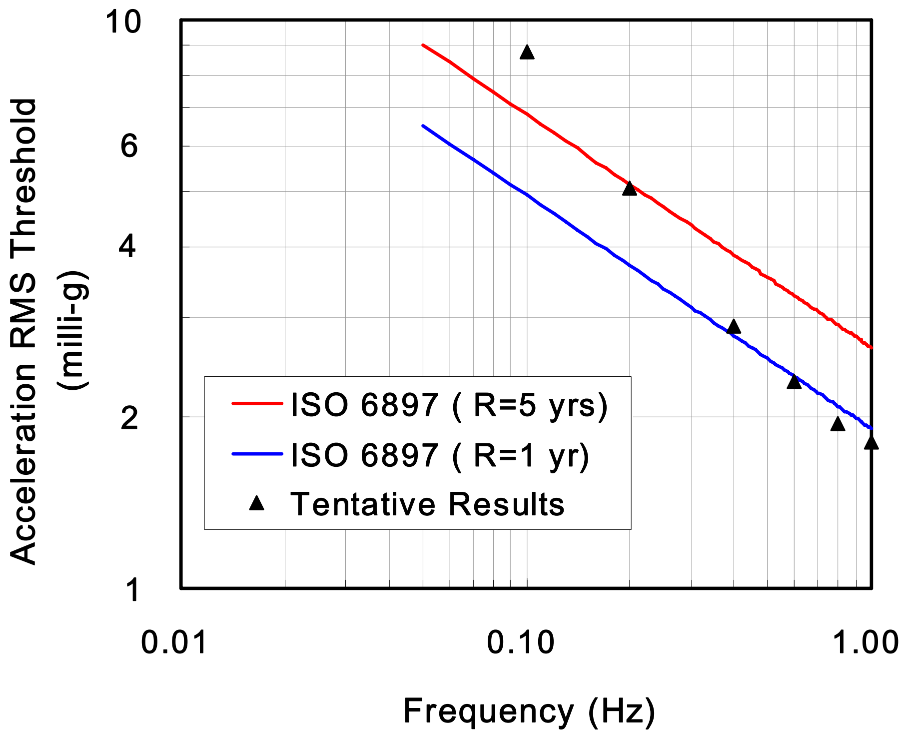

Fig 6: Comparison of Tentative Results of Comfort Thresholds with ISO 6897

CONCLUSIONS

In an attempt to build up the local data base in preparation for improving the Taiwan building wind code in the future, this research project aims to conduct surveys to investigate the comfort criteria by using a motion simulator newly constructed at the wind engineering research center, Tamkang University. In this preliminary study, the methodology and feasible procedure to determine the comfort threshold and the return period for the continuous researches in the long run has been constructed. The tentative results following the procedure were presented, however, a definitive conclusion is not as yet reached until sufficient samples can be collected in the on-going research.

ACKNOWLEDGEMENT

The authors wish to express their gratitude to the financial support from National Science Council of Taiwan under the grant number NSC93-2745-E-032-007.

REFERENCES

Architecture and Building Research Institute of Taiwan (2007), *Taiwan Building Wind Code*, Taipei, Taiwan.

Architectural Institute of Japan (2004), *Guidelines for the evaluation of habitability to building vibration, AIJES-V001-2004*, Tokyo, Japan.

Burton, M. D., Kwok, K. C, S., Hitchcock, P. A. and Denoon, R. O. (2006), "Frequency Dependence of Human Response to Wind-Induced Building Motion", *ASCE Journal of Structural Engineering*, Vol.132, No. 2, pp. 296-303.

Chen, P. W. and Robertson, L. E. (1972), "Human Perception Threshold of Horizontal Motion", *ASCE Journal of Structural Division*, Vol. 98, No. ST8, pp. 1681-1695, 1972.

Denoon, R. O., Letchford, C. W., Kwok, K. C. S. and Morrison, D. L., (1999), "Field Measurements of Human Reaction to Wind-Induced Building Motion", *Proc. of 10th International Conference on Wind Engineering*, Copenhagen, Denmark, pp. 637-644.

Goto, T. (1975), "Research on Vibration Criteria from the View Point of People Living in Tall Buildings. (Part 1) Various Responses of Humans to Motion", *Transactions of the Architectural Institute of Japan*, Vol. 237, No. 11, pp.109-118.

Goto, T. (1983), "Studies on Wind-Induced Motion of Tall Buildings Based on Occupants' Reactions", *Journal of Wind Engineering and Industrial Aerodynamics*, Vol. 13, pp. 241-252.

Hansen, R.J., Reed, J. W. and Vanmarcke, E. H., "Human Response to Wind-induced Motion of Buildings", *ASCE Journal of Structural Division*, Vol. 99, No. ST7, pp. 1589-1605, 1973.

International Organization for Standardization (1984), *Guidelines for the evaluation of the response of occupants of fixed structures, especially buildings and off-shore structures, to low-frequency horizontal motion (0.063 to 1 Hz), ISO6897-1984*, Geneva, Switzerland.

Irwin, A. (1978), "Human Response to Dynamic Motion of Structures", *The Structural Engineer*, Vol. 56A , No. 9, pp. 237-244.

Irwin, A. (1986), "Motion in Tall Buildings", *Proceedings of Conference on Tall Buildings and Urban Habitat - Second Century of the Skyscraper*, Van Nostrand, Chicago, pp. 759-778.

Isyumov, N. (1993), "Criteria for Acceptable Wind-Induced Motions of Tall Buildings", *Proceedings of International Conference on Tall Buildings, Council on Tall Buildings and Urban Habitat*, Rio de Janeiro.

Isyumov, N. and Kilpatrick, J. (1996), "Full-Scale Experience with Wind-Induced Motions of Tall Buildings", Procceedings of *ASCE Structures Congress*, Chicago, USA.

Jeary, A. P., Morris, R. G.. and Tomlinson, R. W. (1988), "Perception of Vibration – Tests in a Tall Building", *Journal of Wind Engineering and Industrial Aerodynamics*, Vol. 29, pp.361-370.

Kanda, J., Tamura, Y. and Fujii, K., (1988), "Probabilistic Criteria for Human Perception of Low-Frequency Horizontal Motions, *Proceedings of Symposium/Workshop on Serviceability of Buildings*, Ottawa, pp. 260-269.

Khan, F. R. and Parmelee, R. A. (1971), "Service Criteria for Tall Buildings for Wind Loading", *Proceedings of 3rd International Conference on Wind Effects on Buildings and Structures*, Tokyo, Japan, pp. 401-407.

Kwok, K. C. S., Burton, M. D. and Hitchcock, P. A. (2007), "Occupant Comfort and Perception of Motion in Wind-Excited Tall Buildings", *Proc. of 12th International Conference on Wind Engineering*, Cairns, Australia, pp. 101-115.

Melbourne, W. H. and Cheung, J.C.J. (1988), "Designing for Serviceable Accelerations in Tall Buildings", Proceedings of *4th International Conference on Tall Buildings*, Hong Kong and Shanghai, pp. 148-155.

Melbourne, W. H. (1998), "Comfort Criteria for Wind-Induced Motion in Structures", *Structural Engineering International 1/98*, International Association of Bridge and Structural Engineering, pp. 40-44.

Shioya, K. and Kanda, J. (1993), “Human Perception Thresholds of Horizontal Motion”, *International Colloquium on Structural Serviceability of Buildings*, Göteborg, Sweden, IABSE Reports, Vol. 69, pp. 45-52.
Standards Australia/ Standards New Zealand (2002), *AS/NZS 1170.2 Supplement 1:2002, Structural Design Actions - Wind Actions - Commentary (Supplement to AS/NZS 1170.2:2002)*, Sidney, Australia.