The 3rd International Conference on Structural Health Monitoring of Intelligent Infrastructure
Vancouver, British Columbia, Canada
November 13-16, 2007

SYSTEM IDENTIFICATION OF CONSTRUCTED BUILDINGS: CURRENT STATE-OF-THE-ART AND FUTURE DIRECTIONS

Tracy L. Kijewski-Correa
University of Notre Dame, USA

Jennifer Cycon
University of Notre Dame, USA

Abstract

This study surveys current efforts directed toward monitoring and system identification of constructed buildings for a wide range of applications, including validation of design practice and damage detection. Given the diversity of structural system form and function, as well as the varying constraints of practical data acquisition systems and the variety of excitation sources serving as inputs to these systems, it is no wonder that a broad spectrum of system identification methods have surfaced. A cross section of methods that have been successfully employed in the analysis of actual building data under naturally occurring excitations is presented herein. Both direct (physical) and indirect (modal) system identification methods executed in the time and frequency domains are overviewed, as are their abilities to accommodate time-variant features often encountered in actual applications. The successes and challenges encountered in these applications then serve as the basis for this study's recommendations of future areas where research efforts are most needed, particularly in the context of structural health monitoring and embedded wireless sensing platforms.

INTRODUCTION

System identification of constructed facilities has been essential to the full-scale validation of existing design practice, providing important information on the in-situ dynamic properties and their variations under a range of loading conditions. However, the need for reliable system identification of constructed facilities has been particularly heightened in recent years due to the growing interest in Structural Health Monitoring (SHM) and has certainly been advanced by measures such as the Building Occupancy Resumption Program (BORP) and California Strong Motion Instrumentation Program (CSMIP). As such, now is an opportune time to define the current state-of-the-art and trajectory of future research efforts in this field.

Today's constructed facilities manifest diversity in both form and function and as such the properties best characterizing these systems are equally diverse. Coupling this with the varying constraints of practical data acquisition systems (e.g., limited instrumentation points, noise, sensor accuracy) and the variety of excitation sources serving as inputs to these systems (measured input vs. unknown input), it is no wonder that a broad spectrum of system identification methods have surfaced [1]. As such, this study cannot encompass all of these efforts, but will provide an overview of methods that have been successfully employed in the *analysis of constructed buildings* under both ambient/wind and earthquake excitations. The successes and challenges encountered in these applications then serve as the basis for this study's commentary on future needs.

Before presenting the current state-of-the-art, some preliminary definitions are required. Since the choice of system identification method is largely driven by the user need and the data available (e.g., recorded output only or measurements at limited locations), the presented methods will be first distinguished by input type: known input (earthquakes) and unknown input (ambient/wind). Beyond this basic distinction, system identification methods can be further sub-classified in a number of ways. Herein, methods will be distinguished according to their treatment of the equation of motion. "Direct" methods are those that operate in the physical coordinate space to yield the *structural parameters* of mass (**m**), stiffness (**k**) and damping (**c**) directly. "Indirect" methods yield *modal parameters* of mass (**M**), stiffness (**K**) and damping (**C**) or more commonly their by-products, frequencies of vibration (f_n), critical damping ratios (ξ) and mode shapes (ϕ), for one or more of the vibrational modes.

Again, this paper will direct its attention toward methods that have been successfully applied to actual constructed buildings under natural loadings and not controlled experiments (at any scale), benchmarks or other simulations. These buildings are summarized in Table 1, along with their abbreviations. Many of the applications that will be discussed herein are in California and often are a result of CSMIP. Unfortunately, without concerns regarding survivability performance or code/policy-based incentives, there is little monitoring activity for US buildings outside of seismic zones. In many instances, monitoring is only undertaken in response to some undesirable behavior and the data acquired is rarely published or is disclosed anonymously.

SYSTEM IDENTIFICATION WITH MEASURED INPUT

Perhaps the single driving factor in the selection of a system identification method is the availability of measured input, which in practice is generally only the case in earthquake applications.

Table 1. Summary of instrumented buildings considered in this study.

Building	Location	Ht. [m]	Type	No. of Sensors/ Recorded Events
A-Chicago [3 Buildings]	Chicago	--	S, RC	4/AV since 2002
A-7	--	7-ST	RC	29/Chi-Chi EQ
A-13	--	13-ST	--	15/Whittier Narrows EQ (1987)
A-22	Viña del Mar, Chile	22-ST	RC	Central Chile (1985)
A-30	Hong Kong	120	S/RC	2/AV since 1995
A-47	San Francisco	172	S	18/Loma Prieta EQ (1989)
A-54	Los Angeles	221	S	20/Northridge EQ (1994)
A-57	Boston	245	S	8/AV 1973-1978
A-73	Seoul	264	RC	6/AV since 2005
Alhambra (AL) Bldg.	Los Angeles	13-ST	S	12/Asst. EQs
Atwood (AW) Bldg.	Anchorage, AK	80.5	S	32/Asst. EQs
Bank of California (BofC) Bldg.	Los Angeles	12-ST	RC	9/San Fernando EQ (1971)
Bank of China (BPRC)	Hong Kong	370	S/RC	2/T. Sally (1996)
Building C	Hong Kong	218	RC	2/T. Imbudo (2003), T. Dujuan (2003)
Building E	Hong Kong	206	RC	2/T. Imbudo (2003), T. Dujuan (2003)

Central Plaza Tower (CPT)	Hong Kong	374	RC	2/T. Sally (1996)
CSUH Admin. Bldg.	Hayward, CA	61	S	16/Loma Prieta EQ (1989)

Table 1. Summary of instrumented buildings considered in this study (con't)

Di Wang Tower (DWT)	Shenzen, PRC	384	S/RC	2/T. Sally (1996)
Fire Cmd. & Control (FCC) Bldg.		9.75	S	16/Northridge EQ (1994)
Guangdong Intl. Bldg. (GIB)	Guangzhou, PRC	200	RC	2/AV
Imperial Co. Services (ICS) Bldg.	El Centro, CA	6-ST	--	13/Imperial Valley (1979)
Jin Mao Tower (JMT)	Shanghai	365	S/RC	2/T. Rananim (2004)
Millikan Library (ML)	Pasadena, CA	43.9	RC	36/Whittier Narrows (1987)
Pacific Park Plaza (PPP)	Emeryville, CA	94	RC	21/Loma Prieta (1989)
Republic Plaza (RP)	Singapore	280	S/RC	4/21 Minor EQ
San Bruno Office Bldg. (SBR)	San Bruno, CA	24	RC	13/Loma Prieta (1989)
Santa Clara Co. Office Bldg (SCCOB)	San Jose, CA	57	S	23/Loma Prieta (1989)
Sylmar Co. Hospital (SCH)		6-ST	RC/S	13/Northridge (1994)
Transamerica Bldg. (TRA)	San Francisco	257	S	22/Loma Prieta (1989)
UCLA Bldg.	Los Angeles	66	S	72/Parkfield (2004)
Union Bank Bldg. (UBB)	Los Angeles	42-ST	S	2/San Fernando EQ (1971)
Van Nuys Hotel (VNH)	Van Nuys, CA	7-ST	RC	16/Big Bear EQ (1992), Northridge EQ(1994)
Japanese Database [205 Buildings]	Japan	< 300	S, RC	≥2/EQ, AV, Forced Vibration
Korean Database [67 Buildings]	Korea	< 243	S, RC	≥2/AV
Italian Database [185 Buildings]	Worldwide	< 337	RC, S	≥2/AV

Notes: RC: Reinforced Concrete, S: Steel, AV: Ambient Vibrations, EQ: Earthquake, T: Typhoon

If available, direct identification of time-varying damping and stiffness matrices is possible, provided the response is measured at all or most of the degrees-of-freedom (DOFs). For example, subspace state-space system identification has been conducted on the 15-story UCLA Building, modeled as a 45-DOF system, utilizing 72 uniaxial accelerometers [2]. While this method generally requires both the measured input and output, it can be used for output-only (ambient) identification by expanding the state space model to generate extra "numerical modes"

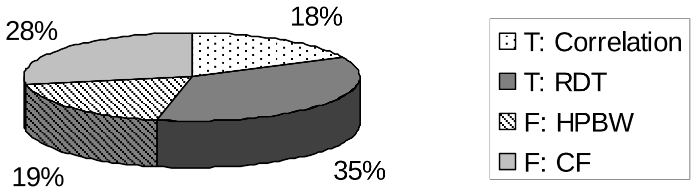

Figure 1. Summary of system identification methods used in
Japanese Damping Database

accounting for the unknown input and noise. A 90th order model was used for the UCLA Building for analysis of ambient vibration data, necessitating additional stability analyses. While the response at uninstrumented degrees-of-freedom can be generated by interpolation or state-space observers, as in the case of the FCC building [3], the limited number of sensors in most large-scale applications often prohibits a unique determination of stiffness and damping matrices. Thus, indirect methods tend to be more popular in practice, as they permit all “visible” modes to be determined uniquely at each measurement point, where the term visible implies that the higher modes are sufficiently excited and not obscured by noise.

Irregardless of whether direct or indirect system identification methods are employed, the availability of measured input enhances the range of viable identification schemes and can even allow time-varying modal properties to be extracted accurately from as little as a two cycles of oscillation. Most of these schemes can be viewed as some form of objective function minimization, with the distinguishing feature being the objective function adopted and the numerical scheme used for its minimization. For example, considering that a structure may be viewed as a filter, subject to some input (ground motion) and yielding some output (structural accelerations), the identification problem can be treated as a discrete-time filter design, as overviewed in [4]. This approach has been applied to the A-22, ICS, TRA, PPP and BofC Buildings [5-9].

Due to its wide availability in commercial software packages, regressive time-series modeling of the recorded input and output accelerations using least squares minimization and extraction of dynamic properties from the poles of the resulting transfer function has become popular [10]. Various regressive models have been adopted, including ARX: autoregressive model with exogenous input, used for the AW, AL, A-7, A-47, PPP, TRA, SCCOB, SBR and CSUH Buildings [10-13] and the autoregressive moving average model with exogenous input (ARMAX), applied to two steel buildings in Japan, as part of the damping database discussed later [14].

The output-error minimization can be conducted within the modal parameter space itself. This type of least squares minimization of the output (acceleration) errors has been applied to the A-13 and A-47 Buildings [15-16]. Meanwhile, Beck and Jennings [17] offer an output-error minimization of the relative acceleration and the derived relative velocity and displacement, using a modal sweeping scheme for efficient and reliable convergence in applications to the UB Building. Alimoradi, et al. [18] use the same response quantities for their objective function, thought with some normalization, and approach its optimization stochastically via genetic algorithms to accommodate larger numbers of variables and objective function complexity. This technique was applied to extract time-variant dynamic properties from 68 full-scale response cases from a variety of instrumented buildings (A-54, ML, VNH, ICS, SCH) [19]. More simplified applications of transfer-function-based methods in the frequency domain can be noted in linear analyses on RP [20].

SYSTEM IDENTIFICATION WITHOUT MEASURED INPUT

In the context of tall building design, serviceability/habitability limit states generally govern, and as such the ability of the structure to effectively dissipate energy and the designer’s ability to predict this behavior is essential. Therefore, a great degree of the full-scale instrumentation programs focused on serviceability limit states under wind have been established to generate databases of viscous damping ratios for a wide cross section of structural systems. The first was presented by Canadian researchers (165 Buildings), and followed by those assembled by Italian (185 Buildings), Japanese (205 Buildings), and Korean researchers (67 Buildings) [21-24]. Most structures within these

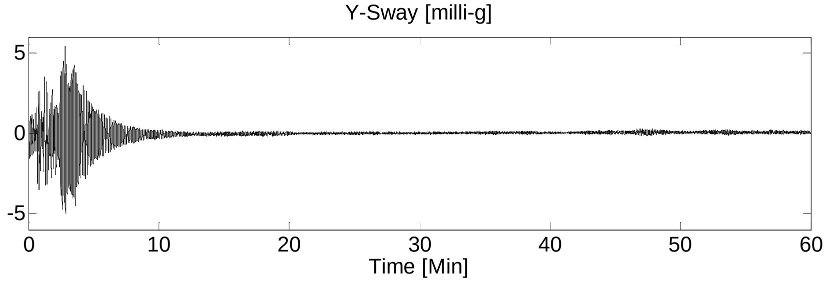

Figure 2. Full-scale response of tall building in Chicago to wind event on June 4, 2005.

databases are excited by ambient vibrations (e.g., wind) for which an input process cannot be recorded. Generally speaking, given the broadband nature of the input spectrum, particularly over the bandwidth of most buildings, assumptions of white noise input are made, and when coupled with assumptions of stationarity and ergodicity, enables the use of a number of “output only” system identification schemes employing temporal averages in lieu of ensembles, though requiring a significant amount of data (tens of hours) to reduce variance [25]. The extraction of dynamic properties in this context may employ either a time domain approach, where logarithmic decay curves are obtained by the direct calculation of the autocorrelation function or proportionally by the Random Decrement Technique (RDT), or a frequency domain analysis, where power spectra are analyzed by the Half Power Bandwidth (HPBW), method of spectral moments, or other curve fitting approaches [22]. A measure of the community’s tendency toward one domain vs. another can be inferred from the Japanese Database, as shown in Figure 1, where 53% of the buildings were identified using time domain methods, largely RDT. This result embodies the community’s shift from the traditional direct generation of the autocorrelation function [21] to the RDT analog [23]. This shift is credited largely to RDT’s practical relaxation of stationarity requirements and its ability to track amplitude-dependent dynamic properties [26]. RDT has been applied, with varying refinements, to a number of the instrumented buildings in China: A-30, DWT, BPRC, CPT, JMT and GIB, four tall buildings in the US, and a tall building in Korea [27-35].

Still the most conventional analysis used in ambient vibration system identification is the power spectral analysis by peak-picking and HPBW, as evidenced by the extensive examples in the European and Japanese databases [22-23] and the analysis of Buildings C and E under typhoons [36]. In fact, in many studies, time and frequency domain results are presented in tandem to underscore inherent trade-offs in bias and variance, e.g., [34]. More detailed comparisons of the identified properties of 22 reinforced concrete buildings from the Korean database using three methods: RDT, HPBW and spectral curve fitting by maximum likelihood estimator (MLE), have been presented to highlight, in particular, the utility of MLE in producing reliable parameter estimates from limited amounts of data [37].

FUTURE NEEDS

The case studies presented herein have highlighted the continued need for accurate indirect identification methods, as practical sensor density in most applications prohibits direct system identification. In general, the common theme amongst applications is *robustness*. Any proposed method should be *robust*, i.e., minimize the sensitivity to model order and/or initial conditions, converging reliably and quickly, and be capable of identifying closely-spaced vibrational modes. Specifically in the case of ambient vibration detection, there is a need for more accurate damping estimates. This has generally required extensive amounts of stationary data (20+ hours of data for the analysis of lightly damped, long period structures), and yet still, damping is often identified low certainty. Specifically, due to the interest in tracking amplitude-dependent properties, the ability to identify damping accurately in strong or transient wind events has been prohibited to date due to a lack of sufficient stationary data (Fig. 2). As such, new identification methods *robust* enough to accommodate weakly stationary or even non-stationary wind events are needed. Time-frequency analysis approaches offer a possible alternative venue for identification, as shown in the work on the BofC Building and the DWT [38-39]; however, to date these have not been able to yield damping estimates. Therefore, there is a need for reliable system identification methods for “output only” applications, ideally suitable nonstationary data analysis.

Much of the early work in system identification has enabled the rapid developments in SHM, where physical properties of the system, including dynamic properties, are evaluated to make some decision about the integrity of the structure. Thus the needs of the SHM community should equally be considered in the next generation of system identification approaches. To date, the ability to reliably discern damage without knowledge of the operational (input) and environmental conditions on site is yet to be demonstrated in practice. Noise (sensor, operational and environmental) can often lead to false positives; meanwhile, the practical limit on sensor density often results in false negatives. Thus the reliability of these methods must be enhanced if SHM is to be formally adopted. With large scale civil structures in mind, the promise of wireless sensor networks (WSNs) is particularly appealing from a system installation and maintenance perspective. WSNs posses distributed computational capabilities, which can be used to reduce communication and synchronization burdens by conducting system identification (damage detection) at the sensor node. This implies that indirect system identification methods, capable of handling the hardware constraints on sensitivity/resolution, computational resources and especially power, are needed. Particularly with respect to the latter two points, system identification approaches embedded in the network must be *robust* enough to distinguish actual damage from environmental and operational variability, subject to the aforementioned hardware limitations, while using limited amounts of data and mathematical operations to maximize battery life as much as possible. Thus some of the most significant future development challenges for system identification may indeed reside in the field of SHM.

REFERNCES

1. Doebling, S.W. and Farrar, C.R., ‘The State of the Art in Structural Identification of Constructed Facilities’, Report by the ASCE Committee on Structural Identification of Constructed Facilities (ASCE, 1999).
2. Skolnik, D., Lei, Y., Yu, E. and Wallace, J., ‘Identification, model updating, and response prediction of an instrumented 15-story steel-frame building’, EQ Spectra 22(3)(2006) 781-802.
3. Nagarajaiah, S. and Li, Z., ‘Time segmented least squares identification of base isolated buildings’, Soil Dyn. & EQ Eng. 24 (2004) 577-586.
4. Safak, E., ‘Adaptive modeling, identification, and control of dynamic structural systems. I: theory’, J. Eng. Mech. 115 (11)(1989) 2386-2405.
5. Safak, E., ‘Adaptive modeling, identification, and control of dynamic structural systems. II: applications’, J. Eng. Mech. 115 (11)(1989) 2406-2425.
6. Safak, E. and Celebi, M., ‘Seismic response of Transamerica Building: part II system identification’, J. of Str. Eng. 117 (1991) 2405-2425.
7. Safak, E. and Celebi, M., ‘Recorded seismic response of Pacific Park Plaza: part II- system identification’, J. of Str. Eng. 118 (1992) 1566-1589
8. Safak, E., ‘Identification of linear structures using discrete-time filters’ J. of Str. Eng. 117 (10)(1991) 3064-3085.
9. Safak, E., ‘Response of a 42-story steel-frame building to the Ms=7.1 Loma Prieta Earthquake’, Eng. Str. 15 (1993) 403-421.
10. Celebi, M., ‘Seismic response of eccentrically braced tall building’, J. of Str. Eng. 119(4)(1993) 1188-1205.
11. Celebi, M., ‘Recorded earthquake responses from the integrated seismic monitoring network of the Atwood building, Anchorage, Alaska’, EQ Spectra 22 (4)(2006) 847-864.
12. Rodgers, J. and Celebi, M., ‘Seismic response and damage detection analyses of an instrumented steel moment-framed building’, J. of Str. Eng. 132 (10)(2006) 1543-1552.
13. Celebi, M., ‘Comparison of damping in buildings under low-amplitude and strong motions’, J. Wind Eng. & Ind. Aero. 59(1996) 309-323.
14. Saito, T. and Yokota, H., ‘Evaluation of dynamic characteristics of high-rise buildings using system identification techniques’, J. Wind Eng. & Ind. Aero. 59 (1996) 299-307.
15. Loh, C. and Tou, I., ‘A system identification approach to the detection of changes in both linear and non-linear structural parameters’, EQ Eng. & Str. Dyn. 24 (1995) 85-97.
16. Li, Y. and Mau, S., ‘A case study of mimo system identification applied to building seismic records’, EQ Eng. & Str. Dyn. 20 (1991) 1045-1064.

17. Beck, J. and Jennings, P., ‘Structural identification using linear models and earthquake records’, EQ Eng. & Str. Dyn. 8 (1980) 145-160.
18. Alimoradi, A., Miranda, E., Taghavi, S. and Naeim, F., ‘Evolutionary modal identification utilizing coupled shear-flexural response-implication for multistory buildings. part I: theory’, The Str. Design of Tall Bldgs. 15 (2006) 51-65.
19. Alimoradi, A. and Naeim, F., ‘Evolutionary modal identification utilizing coupled shear-flexural response-implication for multistory buildings. part II: application’, The Str. Design of Tall Bldgs. 15 (2006) 67-103.
20. Brownjohn, J.M.W., and Pan, T.C., ‘Response of tall buildings to weak long distance earthquakes’, EQ Eng. & Str. Dyn. 30(2001) 709-729.
21. Davenport, A.G. and Hill-Carroll, P., ‘Damping in tall buildings: its variability and treatment in design’, in ‘Building Motion in Wind’, Isyumov, N. and Tschanz, T., Eds. (ASCE, NYC, 1986) 42-57.
22. Lagomarsino, S. and Pagnini, L.C., ‘Criteria for Modeling and Predicting Dynamic Parameters of Buildings’, Report ISC-II, 1-95 (Instituto di Scienza Delle Costruzioni, Universita di Genoa, Facolta di Ingegneria, 1995).
23. Satake, N., Suda, K., Arakawa, T., Sasaki, A., and Tamura, Y., ‘Damping evaluation using full-scale data of buildings in Japan’, J. of Str. Eng. 129(4)(2003) 470-477.
24. Yoon, S.-W. and Ju, Y.-K., ‘Dynamic properties of tall buildings in Korea’ in Proceedings of CTBUH 2004, Seoul, Korea, Oct 2004 (CD-ROM).
25. Littler, J.D., (1995) ‘An assessment of some of the different methods for estimating damping from full-scale testing’, J. Wind Eng. & Ind. Aero. 57 (1995) 179-189.
26. Tamura, Y. and Suganuma, S.-Y., ‘Evaluation of amplitude-dependent damping and natural frequency of buildings during strong winds’, J. Wind Eng. & Ind. Aero. 59(1996) 115-130.
27. Li, Q.S., Xiao, Y.Q., Wong, C.K. and Jeary, A.P., ‘Field measurements of typhoon effects on a super tall building’, Eng. Str. 26 (2004) 233-244.
28. Li, Q.S., Yang, K., Wong, C.K. and Jeary, A.P., ‘The effect of amplitude-dependent damping on wind-induced vibrations of a super tall building’, J. Wind Eng. & Ind. Aero. 91(2003) 1175-1198.
29. Li, Q.S., Xiao, Y.Q. and Wong, C.K., ‘Full-scale monitoring of typhoon effects on super tall buildings’, J. of Fluids & Str. 20 (2005) 697-717.
30. Fang, J.Q., Li, Q.S., Jeary, A.P. and Liu, D.K., ‘Damping of tall buildings: its evaluation and probabilistic characteristics’, The Str. Design of Tall Bldgs. 8 (1999) 145-153.
31. Li, Q.S., Fu, J.Y., Xiao, Y.Q., Li, Z.N., Ni, Z.H., Xie, Z.N. and Gu, M., ‘Wind tunnel and full-scale study of wind effects on China’s tallest building’, Eng. Str. 28 (2006) 1745-1758.
32. Li, Q.S., Wu, J.R., Liang, S.G., Xiao, Y.Q. and Wong, C.K., ‘Full-scale measurements and numerical evaluation of wind-induced vibration of a 63-story reinforced concrete tall building’, Eng. Str. 26 (2004) 1779-1794.
33. Kijewski, T., Brown, D. and Kareem, A., ‘Identification of dynamic properties of a tall building from full-scale response measurements’, in Proceedings of 11th International Conference on Wind Engineering, Lubbock , TX , June 2003 (CD-ROM).
34. Kijewski-Correa, T., Kilpatrick, J., Kareem, A., Kwon, D.K., Bashor, R., Kochly, M., Young, B.S., Abdelrazaq, A., Galsworthy, J., Isyumov, N., Morrish, D., Sinn, R.C. and Baker, W.F., ‘Validating the wind-induced response of tall buildings: a synopsis of the Chicago full-scale monitoring program’ J. of Str. Eng. 132 (10)(2006) 1509-1523.
35. Pirnia, J.D., Kijewski-Correa, T., Abdelrazaq, A., Chung, J. and Kareem, A., ‘Full-scale validation of wind-induced response of tall buildings: investigation of amplitude-dependent dynamic properties’, in ASCE Structures Congress, Long Beach, CA, May 2007 (CD-ROM).
36. Campbell, S., Kwok, K.C.S. and Hitchcock, P.A., ‘Dynamic characteristics and wind-induced response of two high-rise residential buildings during typhoons’, J. Wind Eng. & Ind. Aero. 93 (2005) 461-482.
37. Erwin, S., Kijewski-Correa, T. and Yoon, S.-Y., ‘Full-scale verification of dynamic properties from short duration records’, in ASCE Structures Congress, Long Beach, CA, May 2007 (CD-ROM).
38. Hou, Z., Noori, M. and Amand, R., ‘Wavelet-based approach for structural damage detection’, J. Eng. Mech. 126 (7)(2000) 677-683.
39. Xu, Y., ‘System identification and structural damage detection: EMD + HT approach’, in ‘Structural Health Monitoring and Intelligent Infrastructure’, Proceedings of the 2nd International Conference on Structural Health Monitoring of Intelligent Infrastructure, Shenzhen, China, November 2005 (Taylor & Francis Group plc, London, UK, 2006) 207-217.