Journal of Intelligent Material Systems and Structures

http://jim.sagepub.com

Miniature Free-Fall Sensors

Yu-Hsiang Hsu and Chih-Kung Lee

Journal of Intelligent Material Systems and Structures 2001; 12; 223
DOI: 10.1106/H1HM-4R56-HENF-MFK9

Miniature Free-fall Sensors

YU-HSIANG HSU AND CHIH-KUNG LEE*

Institute of Applied Mechanics, National Taiwan University, No. 1, Sec. 4, Roosevelt Road, Taipei, Taiwan 106, Republic of China

ABSTRACT: This paper describes an attempt to integrate the smart structure concept to the field of high-density data storage devices such as magnetic disk drives, optical disk drives, CDs (compact disks), and DVDs (digital versatile disks), etc. With the rapid development of the data storage industry, methodologies that can be used to sense vibration, free-fall, and impact have been actively pursued throughout the last two decades. As data storage devices are now moving into portable applications, early detection of impact or free-fall has increasingly become more important. Based on this major issue, the concept of measuring the motion of the required free-fall is re-examined. In this article, it is shown that a fundamental characteristic of a free-fall motion, which is the acceleration from zero to one in gravity unit, will be introduced to provide the warning signal for data storage devices. The design concept and the experimental result of this miniature free-fall sensor will be detailed.

INTRODUCTION

ALMOST all previous vibration sensing attempts for portable storage devices have been concentrated on detecting the impact at the instant when the portable storage device hits the ground in order to feed the impact induced signal back to the system for its protective action (Ottesen, 1987). One of the most important protection attempts is taking the read-write head to a safe position in order to prevent catastrophic impact to the media and the read-write head, which may possibly occur when the impact-induced elastic wave arrives (Menon and Gupta, 2000). A simple analysis can show this attempt has almost no chance of becoming successful for the data storage devices adopted in today's notebook computers or digital still cameras. Taking hard disk drives as an example, the seek time that measures the time needed for the read-write head to move 3 cm is approximately 10 ms. An impact-induced elastic wave will have a propagation speed in the range of 3000–5000 m/s. This indicates that the time between the impact and the read-write head experienced the impact-induced wave is in the range 10–30 μs. The astounding three orders of time difference clearly states that a new line of thinking must be initiated. As optical disk drives, CDs/DVDs, etc., have a much slower seek time, this observation certainly is applicable as well. Accelerometers have always been considered as one of the most important vibration-sensing devices due to their size, sensitivity, and cost. However, the traditional design concepts of accelerometers fail to accomplish this goal as gravity induced acceleration will always be present throughout the free-fall. To accomplish the above-mentioned task, an innovative free-fall sensor developed by using the characteristics of flexible structures will be presented in this paper.

CONCEPTS OF FREE-FALL SENSORS

The time history of free-fall motion has previously never been examined in detail. The majority of the studies on impact detection have been concentrated on detecting the information generated by the impact wave induced when the object hits the ground. It is expected that the signal detected can be sent to the system controller to provide the actions needed for the system to protect itself (Ottesen, 1987). As all design goals of today's portable devices are based on being small and fast, the impact protection issue mentioned above is becoming more and more important. As previously mentioned, as impact waves take only 10–30 μs to arrive at the delicate portion of the portable device which requires the impact protection, the signal obtained after the impact occurs, is too late to allow the system to protect itself. Compared to the tenth microsecond shock arrival time, even for high speed devices such as hard disk drives that have a seek speed in the range of 3 cm per 10 ms, it is not fast enough to escape from the damage induced by the impact. The overall strategy related to the impact detection must thus be revisited.

Considering the case where a data storage device falls from a height of one meter, the time difference between the beginning of the device falling to impact is around

*Author to whom correspondence should be addressed.
Tel./Fax: (+886) 2 2365-9436. E-mail: cklee@mems.iam.ntu.edu.tw

1045-389X/01/04 0223-06 $10.00/0 DOI: 10.1106/H1HM-4R56-HENF-MFK9

450 ms which is much longer than the 10 msec seek time mentioned above. This simple calculation indicates that a free-fall sensor will have a much better chance of accomplishing the protection tasks mentioned above. The key thought of the free falling sensing introduced herein lies on the fact that the acceleration changes from at rest to a gravity constant g (Lee et al., 1996). That is, the motion of the free-fall is a kind of force function. A ramp function from zero to one gravity can be used to approximate the forcing action. It is with this understanding that the rise of the acceleration can be detected and where the bold attempt described in this article as free-fall was thought to be not detectable. In the following sections, the concepts of flexible structure control will be introduced to a point accelerometer design concept to facilitate the measurement of these kinds of motions.

Free-fall Sensor Design

To measure the kind of low frequency signal as free-fall motion, the sensor structure itself must be very flexible or its first mode frequency must be low enough. The most familiar structure which comes to mind, is the bending vibration of a beam or a plate (Graff, 1975). However as its first mode frequency is low, the noise from the mode will always be present. This observation is a reflection that the performance of the point is determined by the sensor structure. This is also the reason why the usable bandwidth of typical point sensors are merely 5–10% of the first mode frequency. To have enough bandwidth, the first resonant mode of a typical point sensor is often as high as say 10 kHz to several hundred kHz. This effect can be clearly observed in Figure 1, where Channel 1 represents the displacement signal measured by using a photonic sensor, Channel 2 represents the acceleration signal obtained by using a traditional accelerometer with its first resonant mode at 60 kHz. In addition, Channel 3 represents the charge signal obtained from a one-dimensional cantilever piezoelectric plate with it first resonant mode near 10 Hz. It is evident from Figure 1 that the low frequency response of the traditional accelerometer signal is buried within the noise. On the other hand, the low frequency response of the flexible piezoelectric cantilever plate is extremely good. One thing that should be noted is that the 1 Hz vibration signal generated by the one-dimensional plate still suffers from the detrimental effect of the first resonant mode (Figure 1a). This is the reason why the usable bandwidth of a point sensor is restricted by the characteristics of the sensor structure. There does exist some noise induced from the structure natural frequency that will alter the measured input signal waveform and phase. This property can easily be explained by a normal mode expansion of the structure. Considering the bending displacement of a one-dimensional structure (Meirovitch, 1986):

(a)

(b)

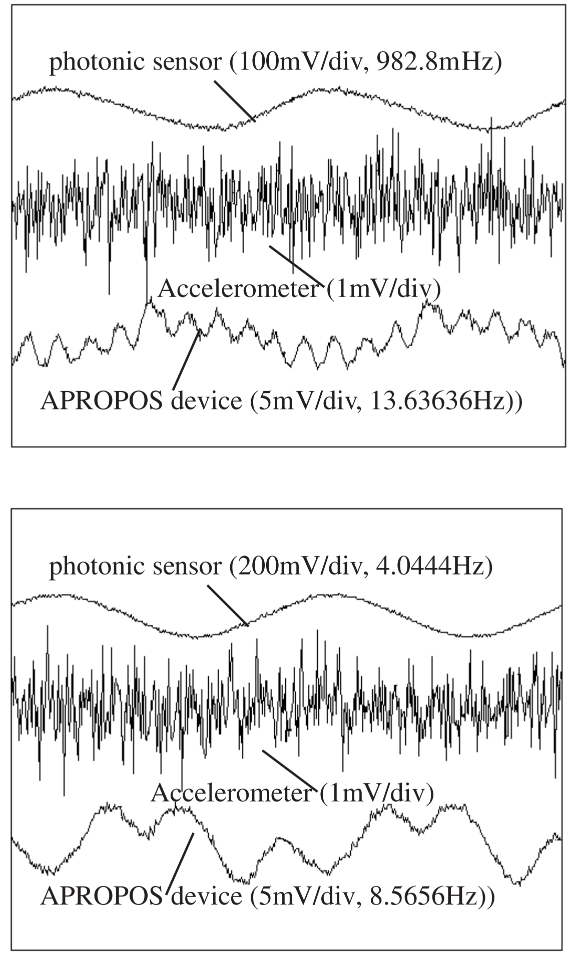

Figure 1. *(a) Comparison of a time domain result from an one-dimensional cantilever plate (Ch3), a photonic sensor (Ch1), and an accelerometer (Ch2) at 10 Hz (a) at 1 Hz (b).*

$$w(x, t) = \sum_{i=1}^{\infty} A_i(t)\Phi_i(x) \quad (1)$$

where $A_i(t)$ is the modal coordinates of the ith mode, and $\Phi_i(x)$ represents the ith mode shape. That is, the vibration of the structure is the combination of the mode shapes at all frequencies. The influence of the modes at different excitation frequencies can be examined by using the modal coordinates $A_i(t)$ mentioned above. As the vibrating frequency moves closer to the natural frequency, the structure vibration behaves similar to that mode. This characteristic holds true for a forced response (Meirovitch, 1986) and this feature strongly influences the measurement data of a free-fall motion. More specifically, once the externally applied force excites the sensor, the sensor structure characteristics will automatically kick in to influence or modify the signal generated. In other words, with the presence of the high frequency response of all of the natural modes, the signal induced by the free-fall response and the system transient response will not be distinguishable. That is, the signal from the free-fall motion is distorted by the noise induced by the natural modes. The above discussion clearly states that the effect of the natural modes must be filtered out to provide a clear free-fall signal free from the contamination of the modal response. It will also be shown later that the interface circuit of the free-fall sensor will influence the performance of the free-fall sensor.

TESTING OF FREE-FALL SENSORS

To test the free-fall motion, the following experimental set-up (Figure 2) was designed to measure the induced signal. A free-fall sensor made by a one-dimensional plate was attached to a piece of a hard disk shaped iron block. An interface circuit was chosen for the free-fall sensor to tailor the free-fall signal generated. The test specimen was allowed to fall through a light switch made of a He–Ne laser and a photovaristor triggered the data taking. A resister ***R*** was chosen to form a voltage divider circuit to serve as the trigger signal for the oscilloscope. With this arrangement, the change in the photovaristor output voltage served as the reference to distinguish the signal induced from the free-fall motion signal from that of the impact signal.

A 50 mm long, 5 mm wide, and 0.01 mm thick standard steel shim was set to form a one-dimensional cantilever plate, which served as the sensor structure. A uniform piezoelectric polymer thin film (polyvinylidene fluoride, PVDF) was attached to this sensor structure to measure the forced response induced by the free-fall motion. The frequency of the first resonant mode of sensor was found to be around 30 Hz, which means that this sensor was easily excited by the external force. The experimental result is shown in Figure 3, where Channel 1 was the trigger signal generated by the photovaristor with a 30% timing pre-trigger, and Channel 4 was the data measured by the PVDF sensor mounted onto the one-dimensional cantilever plate. It is obvious from Figure 3(a) that the three force response events was detected, which in turn represents the responses induced by the beginning of the free-fall, the impact to the ground, and the bounce of the iron block. Also from Figure 3(b), the time lag between the responses induced by the free-fall to the full transient response was about 20 ms, which corresponds to 50–100 Hz. As the first resonant mode was around 30 Hz, the 50–100 Hz external response measured will certainly be contaminated by the first modal response. This experimental data clearly demonstrates that the noise induced by the resonant mode of the sensor structure is a major hindrance for the development of a free-fall sensor as the response induced by the free-fall and by the reaction of the resonant mode is not distinguishable. In other words, the signal generated

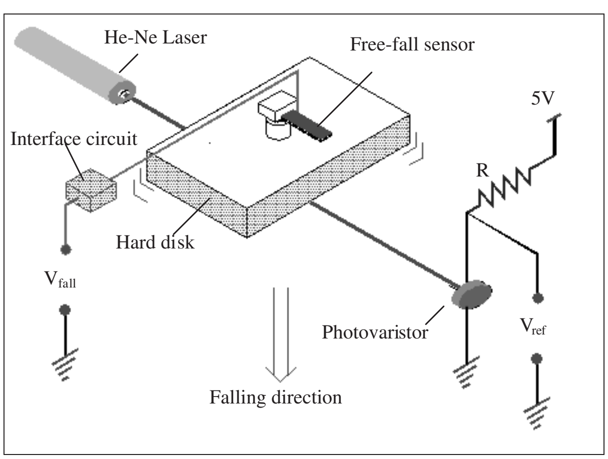

Figure 2. *Experimental set-up for measuring free-fall motion.*

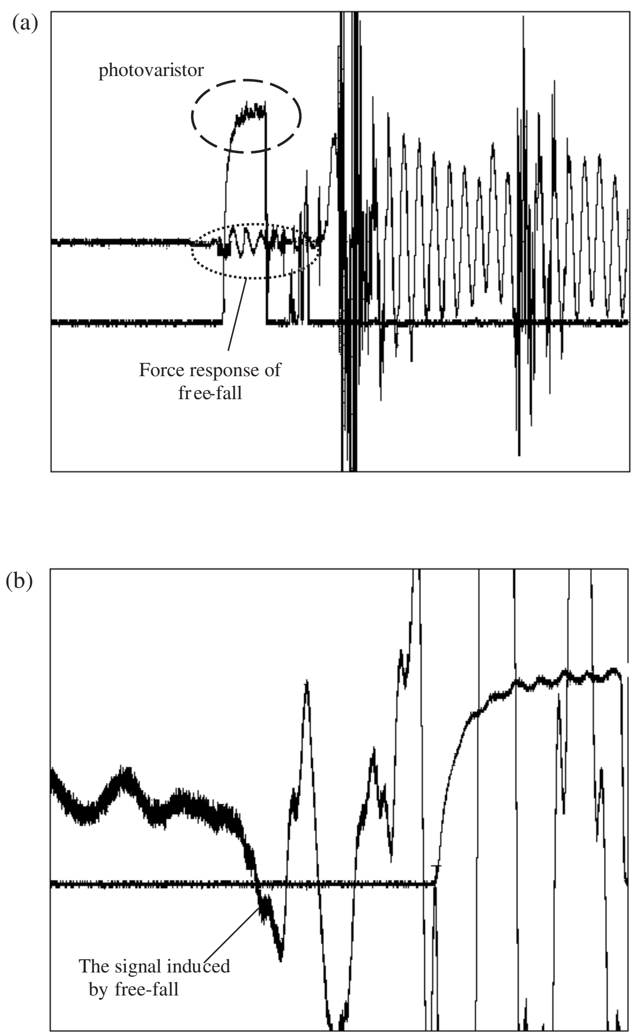

Figure 3. *(a) Response of a free-fall sensor motion; (b) magnified response of a free-fall motion.*

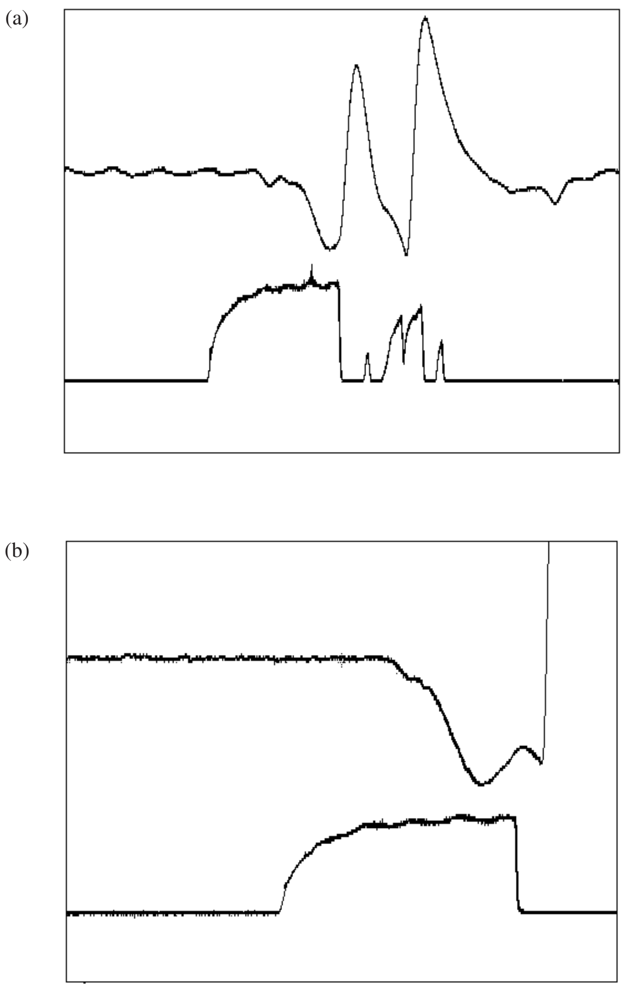

Figure 4. Experimental result of a charge mode free-fall sensor with a –40 dB/decade low-pass filter.

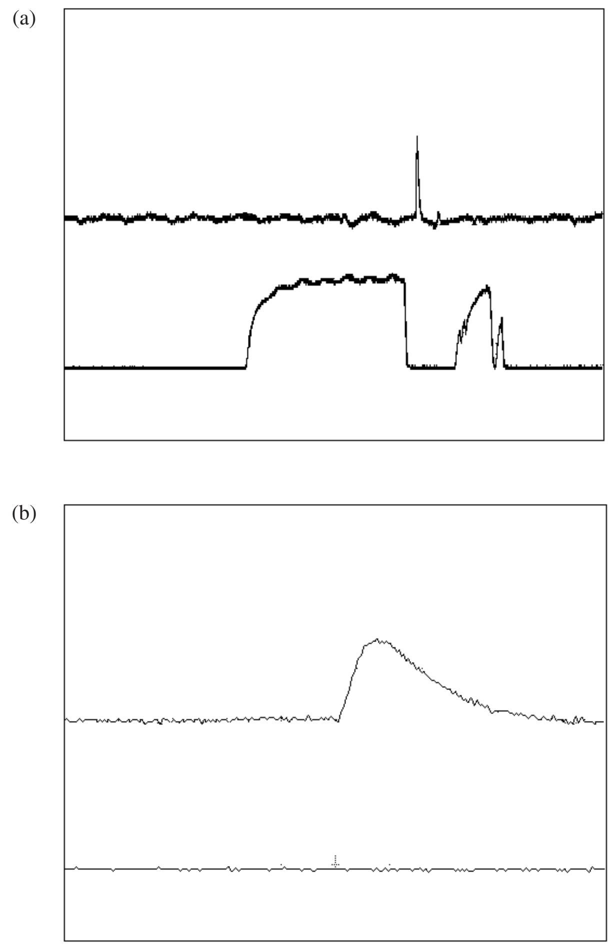

Figure 5. Experimental result of a current mode free-fall sensor with a –40 dB/decade low-pass filter.

was not the result of the free-fall, but as a result of the external disturbance that is always present. In other words, it is not the result of a true free-fall as a true free-fall response cannot be detected when it really occurs. This understanding leads to the conclusion that the noise induced by the reaction of the structure mode must be eliminated or reduced in order to make the free-fall signal stand out.

To minimize the influence of the natural mode, the simplest approach will be to push the first mode frequency higher while at the same time introducing a low-pass filter to further reduce the natural mode effect. To accomplish this goal, a 20.1 mm long, 6 mm wide, and 1.8 mm thick PZT was constructed in a one-dimensional cantilever plate configuration and chosen as the sensor structure where the first mode frequency was set at 1.41 kHz. The experimental results are shown in Figure 4. A charge amplifier and a 2 pole low-pass filter were chosen as the interface circuit. Varying the corner frequency of the low-pass filter, it was discovered that the transient response could be filtered out when the corner frequency was set at 100 Hz. The experimental results are shown in Figures 4(a) and 4(b), where almost all of the transient response is filtered out by the low-pass filter introduced. With the filter in place, the free-fall and the impact response were found to have an exponential decay behavior. It is also clear from the experimental data that the free-fall response is clearly discernable.

Figures 5(a) and (b) are the experimental results obtained when the current amplifier was chosen as the interface circuit, which essentially converted the sensor into an acceleration rate sensor (Lee et al., 1996). It should be noted that a low-pass filter was present and that it appears to influence the final sensor output. The rise time of the current amplifier was set at 0.1 ms, and the corner frequency of the low-pass filter was chosen at 1 kHz. It is clear that a pulse signal was generated by this current amplifier configuration. It should be noted that this pulse was generated as a result of the low-pass filter filtering out the low frequency response of the free-fall sensor. This pulse was induced at the time when the sensor structure began its transient response, which can be seen in Figures 4(a) and (b). Note also that the frequency of the pulse was about 500 Hz. More specifically, the experimental set-up shown in Figure 5 clearly demonstrates that when a current amplifier is used as the interface circuit, a pulse signal due to free-fall can be generated. In other words, with the configuration disclosed here, it is possible to offer a single pulse signal to warn the beginning of a free-fall.

DISCUSSIONS

The experimental results obtained clearly demonstrate the possibility of creating a free-fall sensor. It should be mentioned that the signal is the combined effect of the force response and the interface circuit used. Note also that the sensitivity is highly dependent upon the flexibility of the structure, which can be observed from the differences between the two free-fall sensors developed during the course of this research. The softer free-fall sensor can measure the falling motion earlier while suffering the influence of the transient modal responses. This result clearly demonstrates the importance of setting the first resonant mode frequency of the sensor structure. The higher the chosen first modal frequency, the more the filtering effect can be introduced to distinguish the induced transient modal response. However, setting the first resonant mode frequency higher will certainly reduce the sensor response and may also introduce a milli-seconds time delay. On the other hand, the phase delay introduced by the interface circuit and the low-pass filter adopted also will introduce a time delay to the detected signal. Thus the higher the first mode frequency, the smaller will be the influence on the phase delay induced by the low-pass filter, i.e., a lower influence to the true free-fall response.

The experimental data indicates that a pulse signal can be measured at about 80 ms after the beginning of the free-fall, which translates to around a 370 ms lead time for the data storage device to provide an impact evasive reactive action. As 370 ms is much longer than the average 10 ms seek time of today's read-write head to move out the disk, the suitability of the free-fall sensor developed is thus quite obvious. Taking the prosperous MEMS (Micro-Electrical-Mechanical Systems) technology nowadays as an example, a micro accelerometer with about a kHz first resonant mode is common. Combining the above-mentioned perspectives indicates that taking a free-fall sensor to further improve the shock or impact resilience performance for data storage devices shall not be an impossible task anymore.

To enhance the performance of the free-fall sensor, several key factors should be considered: (1) a good sensor structure flexibility, (2) a low first mode resonant frequency, (3) a proper low-pass filter to filter out the transient modal response, and (4) a negligible phase delay introduced by the interface circuit used. A good free-fall sensor definitely represents a good compromise

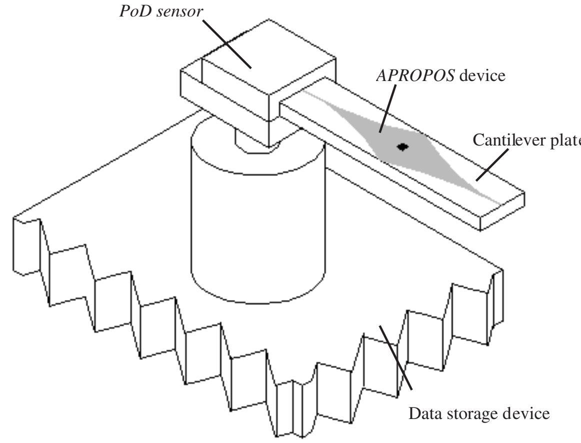

Figure 6. *Schematic of a PoD sensor.*

to all these key points. In the field of flexible structure control, a series of a no phase delay low-pass filter were introduced in the spatial domain by integrating the distributed sensor concept to the development of point sensors, such as with accelerometers. This class of sensors, named *APROPOS* devices (Lee et al., 1999a) and "APROPOS" is an acronym for *A*utonomous *P*hase-gain *RO*tation/linear *P*iezoelectric *O*ptimal *S*ensing, and was first reported at the 10th ICAST conference (Figure 6). This type of sensor was classified as a Point-Distributed sensor (*PoD sensor*). This kind of no-phase delay low-pass filter can filter out the transient modal response without introducing any phase delay. Combining the effects of an *APROPOS* device and a traditional *RC* filter, the first modal frequency of the sensor structure can be further reduced to a negligible level. Taking this approach, the free-fall sensor sensitivity can be further increased while nullifying the time delay introduced by the filter. It should be mentioned again that optimizing the force response of the sensor structure created the free-fall sensor in this article. To further improve the overall sensor response, the true motion of the free-fall device during its fall should be further investigated. A Michelson interferometer type interferometer like that of the Advanced Vibrometer/Interferometer Device (*AVID*) (Lee et al., 1999b; AHEAD, 1999) will be introduced in the future to further unveil the influence of sensor structures to the detection of free-fall motion. In summary, measuring free-fall motions by using accelerometers or acceleration rate sensors have been successfully demonstrated and its influence on the interface circuit has also been verified experimentally.

REFERENCES

AHEAD Optoelectronics, Inc. (1999). AVID, Advanced Vibrometer/Interferometer Device, No. 13 Chin-ho Road, Chung-ho, Taipei hsien 235, Taiwan, R.O.C. (http://www.ahead.com.tw).

Graff, K.F. (1975). *Wave Motion in Elastic Solids*, New York, USA: Dover Publications, Inc.

Hsu, Y.H., Lee, C.K., Hsiao, W.H., Lin, C.T., Shih, H.C., Hsu, S.H. and Hsu, H.S. (October 11–13, 1999). *APROPOS* Device for Control-Structure Interactions. *Proc. 10th International Conference on Adaptive Structures and Technologies (ICAST'99)*, pp. 45–52, Lancaster, Pennsylvania, USA: Technomic Publishing Co., Inc.

Lee, C.K., Hsu, Y.H., Lin, C.T., Hsiao, W.H., Shih, H.C., Hsu, S.H. and Hsu, H.S. (October 11–13, 1999a). Implementing *APROPOS* Device as Point Sensors. *Proc. 10th International Conference on Adaptive Structures and Technologies (ICAST'99)*, pp. 53–60, Lancaster, Pennsylvania, USA: Technomic Publishing Co., Inc.

Lee, C.K., Wu, G.Y., Teng Thomas, C.T., Wu, W.J., Lin, C.T., Hsiao, W.H., Shih, H.C., Wang, J.S., Lin Sam, S.C., Lin Colin, C., Lee, C.F. and Lin, Y.C. (March 1999b). A High Performance Doppler Interferometer for Advanced Optical Storage Systems, *Japanese Journal of Applied Physics*, **38**(3B): 1730–1741.

Lee, C.K., Munce, A.C., Jr., T.C. O'Sullivan (May 28, 1996). Disk Drive with Acceleration Rate Sensing, USA Patent No. 5,521,772.

Menon, A.K., and Gupta, B.K. (2000). *Data Storage for the Millennium*. London, UK: ICG Publishing Ltd.

Meirovitch, L. (1986). *Element of Vibration*. Singapore: McGraw-Hill Inc.

Ottesen (1987). Apparatus for Detecting and Correcting Extensive Vibration in a Disk File. *IBM Technical Disclosure Bulletin*, **30**(6): 81–82.