以數位量測解決環境振動品質問題

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一、前言

精密環境如半導體廠房及先進研究設施，在近年來對於環境振動要求，有越來越嚴謹的趨勢。對於設備的精密姿態控制(Precise attitude control)、短時整定時間(Short settling times)，也有一定的環境振動限制。同時，振動強度會隨著製造設備的生產速度變快以及體型變大而增加。設備裝設樓層高度的提升，普遍對於振動噪音的反制需求也會隨之提升。

由於設備安裝後的降噪措施較為有限，比較有效的方法是在廠房設計施工階段就進行振動評估及監測。另一方面，當振動問題發生於工作場域，則需採取即時的因應策略。相同的振動問題，若發生於客戶端，且源於先前安裝的設備及裝置，於此情形下，對於問題的判讀會較難以釐清，增加解決問題的難度。此時需要合適的方法來找尋原因，這些方法並不是這麼難掌握。藉著高效的加速度規，即使是短短幾分鐘的微振資訊，也能夠提供許多線索，來解決問題。隔振設計同樣也可以藉由量測現地振動程度，來證實是否有達到容許的振動範圍內。振動源的識別則可透過以下對策。

2014年，Epson發表了石英振盪加速度規，藉著其好品質及表現，隨即受到了市場廣大的好評及名聲。本文會介紹振動源識別、振動訊號分析、振動量測的所需工具，以及提供案例，來協助可能會面臨以上問題的人。

二、影響設備精度的振動源

圖1顯示實驗室及工廠的常見振動源，包含了地表振動、營建機械振動、製造設備振動以及工作相關振動。此外，車輛行經、工廠設備運作以及建築施工所造成的振動，都會影響設備精度，結構形式則會影響振動的傳遞。

設施中產生振動的典型機械，包含冷卻機、空調、變壓器、電梯、空調管線以及音響設備。關於製造設備，其中包含小型壓縮機、多種熔爐、加工設備、小型冷卻設備等，皆有可能鄰近於精密設備。工作相關振動的原因包含，人員走動、機械運作以及自動導引車，垂直振動是典型的主要工作振動干擾。[1]

Approach against Quality Problems through Environmental Vibration Digital Measurement

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1. Introduction

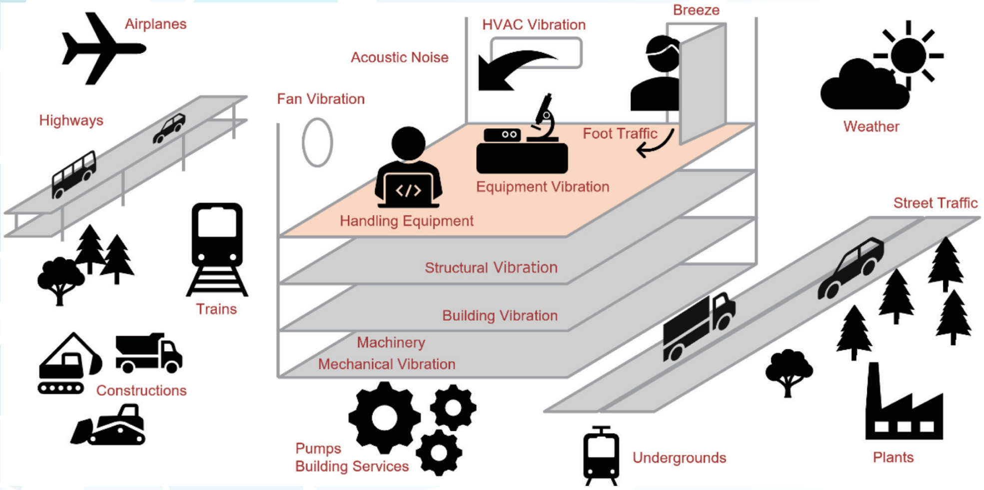
Precision environments such as semiconductor factories and advanced research facilities have required quiet environmental vibrations in recent years, as well as precise attitude control and short settling times for equipment. At the same time, vibration forces of the equipment themselves are increasing as production equipment becomes faster and larger. It is not a rare case for equipment that used to be installed on the ground floor to now be installed on an upper floor, which leads to the growing need for countermeasures against noise and vibration.

Since there are limited ways to deal with vibration problems after the equipment installation, it is more effective to take measures at the facility design stage. On the other hand, when a problem occurs on the worksite, countermeasures must be taken quickly and in line with current conditions. The same goes for the vibration-related problems at the customer site caused by previously installed equipment or devices. This might seem difficult to get a clear view of how to resolve these problems within the constraints of the current situation. You need to use appropriate methods to gain a prospect, and you need to be familiar with using them. Fortunately, these methods are not too difficult to understand. With effective use of accelerometers, even minute vibrations that may not be felt by humans can be detected, and you can obtain clues to solve these problems. The target for vibration isolation design can be justified after understanding the current vibration levels and the vibration tolerances of equipment. The identification of the vibration sources are followed by the countermeasures.

Since Epson developed and launched a quartz crystal accelerometer in 2014, our products have been used in a wide range of applications and have earned an excellent reputation in the market for their quality and performance. This paper will introduce the analysis tools necessary for the identification of vibration sources and the vibration analysis, environmental vibration digital measurement, and provide specific examples to help those who are likely to encounter vibration problems.

2. Vibration Sources that Affect Precision Equipment

Figure 1 shows examples of vibration



▲ 圖1　常見振動源於實驗室及工廠

三、振動評估方法

1. 量化振動大小的三分圖

本文採用三種量化振動大小的物理量，分別為位移、速度以及加速度。簡而言之，考慮一個簡單的單頻弦波(頻率為f)其振幅為D，然後對應之位移、速度以及加速度隨時間的關係式為：

位移：$d(t) = D \cdot \sin(2\pi f^*t)$

Unit：mm、μm

速度：$v(t) = D \cdot 2\pi f \cdot \cos(2\pi f^*t)$ Unit：mm/s、μm/s

加速度：$a(t) = -D \cdot (2\pi f)^2 \cdot \sin(2\pi f^*t)$

Unit：mm/s^2、gal (cm/s^2)、$\mu m/s^2$

gal (cm/s^2) 是一種常見的加速度單位，其對應的單位轉換如下:

($1\ g = 9.80665\ m/s^2 = 980.665 gal$, $1\ gal = 1\ cm/s^2 \fallingdotseq 1.0197 mg$) 註：原文的重力加速度標示為G，其通常表示為重力常數，故本譯文以小寫g表示重力加速度。

如果我們標註速度振幅為V，加速度振幅為A，則D、V、A彼此間的關係，可用以下數學式表示：

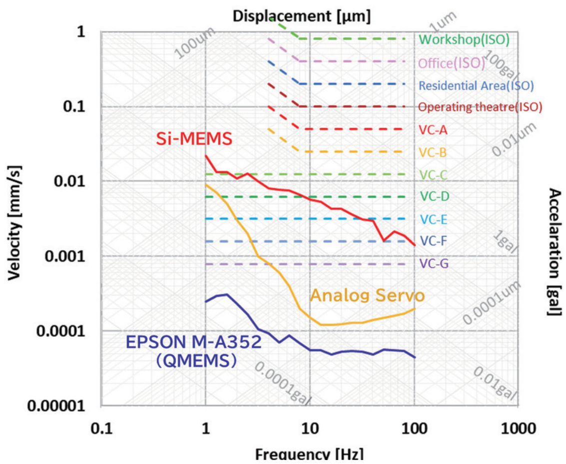
位移振幅：$D = V/(2\pi f) = A/(2\pi f)^2$

速度振幅：$V = D \cdot 2\pi f = A/(2\pi f)$

加速度振幅：$A = D \cdot (2\pi f)^2 = V \cdot 2\pi f$

其中若為峰值到峰值之間的振幅，則會用下標p-p表示，如$D_{p\text{-}p}$、$V_{p\text{-}p}$以及$A_{p\text{-}p}$。

由於D,V以及A之間可以透過以上式子互相轉換，將各振幅值對應於特定頻率，繪於單一平面(三分圖)。如圖2，三項振幅值可以同時的識別於三分圖，此圖通常繪於對數座標上。



▲ 圖2　三分圖與VC Curves

sources in plants and research facilities. Sources of vibration include ground vibration, construction machinery vibration, manufacturing equipment vibration, and work-related vibration. Increasingly, vibration from vehicles on the surrounding roads, the operation of production equipment in factories or buildings, and construction work also affect precision equipment. The structure of the building influences the transmission of vibration from vibration sources.

Typical machines that generate vibrations in facilities include chillers, air conditioners, transformers, elevators, air conditioning ducts, and audio equipment. Regarding the manufacturing equipment, there are small compressors, various furnaces, processing equipment, small cooling equipment, etc., which may be located adjacent to precision equipment. Causes of work-related vibration include walking, robot operations, and automatic guided vehicles. Vertical vibration is one of the major disturbances typical of work vibration [1].

3. Vibration Evaluation Methods

3.1 Yardsticks for the Magnitude of Vibration, Tripartite Graph

There are three yardsticks for the magnitude of vibration; displacement, velocity, and acceleration. For simplicity, considering a single vibration of frequency f and displacement amplitude D, the following relationship holds between displacement x(t), velocity v(t) and acceleration a(t).

displacement：$d(t) = D \cdot \sin(2\pi f^*t)$

Unit：mm、μm

velocity：$v(t) = D \cdot 2\pi f \cdot \cos(2\pi f^*t)$

Unit：mm/s、μm/s

acceleration：$a(t) = -D \cdot (2\pi f)^2 \cdot \sin(2\pi f^*t)$

Unit：m/s^2、gal (cm/s^2)、$\mu m/s^2$

Unit gal (identical to cm/s2) is often used as the unit of acceleration (1 G = 9.80665 m/s2 = 980.665 gal, 1 gal = 1 cm/s2 ～ 1.0197 mG). If we denote the velocity amplitude as V and the acceleration amplitude as A, the following relationship between D, V and A are derived by comparing the coefficients in the above equations,

Displacement amplitude：$D = V/(2\pi f) = A/(2\pi f)^2$

Velocity amplitude：$V = D \cdot 2\pi f = A/(2\pi f)$

Acceleration amplitude：A = D (2πf)2 = V 2πf

where the amplitudes D, V, and A represent peak amplitudes. When peak to peak amplitudes are used, they may be distinguished by the suffix p-p, such as Dp-p, Vp-p and Ap-p.

Since D, V, and A at the vibration frequency f can be converted to each other by the above equation, each amplitude value with respect to the frequency can be plotted in one plane (tripartite graph, Figure 2). Three amplitude values can simultaneously be identified on the tripartite graph. A log-log plot is used for the axes of the tripartite graph in general.

3.2 Evaluation of Environmental Vibrations by Octave Analysis and VC Curves

FFT and octave analysis are used to analyze vibration data. The difference between the two

2. 以八音頻帶分析及振動標準線作環境振動評估

快速傅立葉(Fast FourierTransform, FFT)以及八音頻帶分析(Octave analysis)常用於分析振動資料，其中兩者區別為頻率區間的分割；傅立葉的頻率區間為固定常數，而八音頻帶頻率區間則為固定比例。將一個八度(倍頻)分隔成3、12或24區塊，分別對應於1/3倍頻程、1/12倍頻程、1/24倍頻程分析。每個帶寬之中央頻率及帶通濾波器之特性，定義於ISO 266:1997 以及IEC 61260-1:2014。[2-3]

設備振動標準最早由美國提出，為精密機械之振動容許標準（示於表1），目前也被普遍的採用。[4]基本上，振動標準線（VC curves）是以振動速度去做有效值運算，並繪於1/3八音頻帶分析（示於圖2）。振動標準線是國際標準化組織（International Organization for Standardization，ISO）人體振動標準的延伸（請參考ISO2631：人體全身振動評估標準[5-6]），對於微振區間 (Micro-vibration region)，定義為VC-A到VC-E五條標準線，而每個區間間隔為6dB。於2005年時，振動標準線加入了VC-F以及VC-G，用以評估極度低噪的振動環境。[7]

▼ 表1　環境振動標準解說 [4-7]

Criterion Curve	Description	Amplitude[1)] μm/s (in/s)	Detail Size[2)] μm
Workshop (ISO)	Distinctly perceptible vibration. Appropriate to workshops and non-sensitive areas.	800 (32,000)	N/A
Office (ISO)	Perceptible vibration. Appropriate to offices and non-sensitive areas	400 (16,000)	N/A
Residential Area (ISO)	Barely perceptible vibration. Appropriate to sleep areas in most instances. Usually adequate for computer equipment, hospital recovery rooms, semiconductor probe test equipment and microscopes less than 40x.	200 (8000)	75
Operating Theatre (ISO)	Vibration not perceptible. Suitable in most instances for surgical suites, microscopes to 100X and for other equipment of low sensitivity.	100 (4000)	25
VC-A	Adequate in most instances for optical microscopes to 400X, microbalances, optical balances, proximity and projection aligners, etc.	50 (2000)	8
VC-B	Appropriate for inspection and lithography (including steppers) to 3 μm line widths.	25 (1000)	3
VC-C	Appropriate standard for optical microscopes to 1000X, inspection and lithography inspection equipment (including moderately sensitive electron microscopes) to 1 μm detail size, TFT-LCD stepper/scanner processes.	12.5 (500)	1 – 3
VC-D	Suitable in most instances for the most demanding equipment including electron microscopes (TEMs and SEMs) and E-Beam systems.	6.25 (250)	0.1 – 0.3
VC-E	A challenging criterion to achieve. Assumed to be adequate for the most demanding of sensitive systems including long path, laser-based, small target systems, E-Beam lithography systems working at nanometer scales, and other systems requiring extraordinary dynamic stability.	3.13 (125)	<0.1
VC-F	Appropriate for extremely quiet research spaces; generally difficult to achieve in most instances, especially cleanrooms. Not recommended for use as a design criterion, only for evaluation.	1.56 (62.5)	N/A
VC-G	Appropriate for extremely quiet research spaces; generally difficult to achieve in most instances, especially cleanrooms. Not recommended for use as a design criterion, only for evaluation.	0.78 (31.3)	N/A

1) 此振動標準為1/3八音頻帶頻率區間，採用8到80Hz(用於VC-A以及VC-B)或是1到80Hz(用於VC-C到VC-G)
2) 詳細尺寸(Detail size)是指微電子製造的線寬，醫學和製藥研究中的粒子（單元）尺寸等。給定的值考慮到許多項目的振動要求，取決於加工過程中的細部尺寸。

is the way in which the vibration components are divided into frequency bands; the frequency bandwidth of the FFT is constant, whereas the frequency bandwidth of the octave analysis is divided into constant proportions. The octave is divided into 3, 12 or 24 divisions, which correspond to a 1/3, 1/12 or 1/24 octave band analysis respectively. The values of the center frequency of each band and the slope characteristics of the bandpass filter for octave analysis are standardized in ISO 266:1997 and in IEC 61260-1:2014 [2-3].

VC curves, shown in Table 1, were proposed by the USA as a permissible vibration criterion for precision machinery, and it is commonly adopted for evaluation [4]. Basically, the permissible vibration criterion is defined by the vibration speed, and is judged by plotting the effective value obtained by 1/3 octave band analysis; the VC curve evaluation is an extension of the ISO vibration criterion for the human body (ISO 2631, Evaluation of human exposure to whole-body vibration [5-6]) to the micro-vibration region (VC-A to E), and are specified in 6dB steps. In 2005, VC-F and VC-G were added to the criteria, mainly for evaluation of ultrafine vibration environments [7].

4. Environmental Vibration Digital Measurement using the Quartz Crystal Acceleration Sensor M-A352

When a vibration problem occurs, measures must be taken to address the problem in line with current conditions. Accelerometers are employed to identify the environmental vibration level and vibration sources. Metal springs, air springs, anti-vibration rubbers/pads are used as vibration prevention materials for equipment and machinery. Each material has its proper frequency range for vibration attenuation. It is necessary to determine a target for attenuation amount according to the environmental vibration level and the vibration tolerance of the equipment/ machinery. If vibration prevention materials are not effective, you will need to consider installing a vibration isolation device or system, or employing a floating floor construction. When the vibration from roads, railroads, or surrounding factories is excessive, there are other countermeasures, such as the construction of vibration isolation trenches in the ground around the building [1]. This paper will not go into such details.

To confirm that the target level of prevention and isolation is reached by countermeasures, the environ- mental vibration levels before and after the countermeasures are compared. Environmental vibration digital measurement can be performed easily and quickly by using the quartz crystal acceleration sensor M-A352.

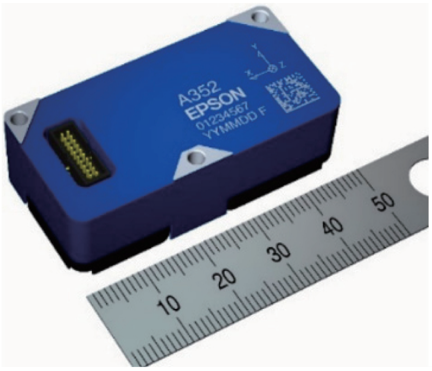
4.1 Quartz Crystal Accelerometer M-A352

The M-A352 is a high-performance triaxial quartz crystal accelerometer that achieves a dynamic range of ±15G, low noise of 0.5 μG/√Hz, rms, and high resolution output of 0.06μG/LSB (Figure 3). The M-A352 provides

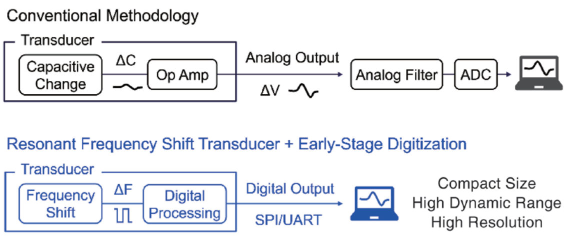
四、環境振動數位量測採用石英振盪加速度規M-A352

當振動問題發生，就必需採取合宜的測量方法。 加速度規的採用，就是為了識別出環境振動大小以及振動來源。 金屬彈簧、空氣彈簧、抗振橡膠/抗振墊，為機械設備常用的防振材質。每種材質有其適當的頻率區間用於減振。機器設備根據環境振動大小及容許值，以決定目標減振程度是相當重要的。若防震材質效果不佳，則可以考慮採用隔震設備、系統或是浮式結構。 若振動來源為街道、鐵路或周遭工廠，則有其他的對應策略，像是槽溝減振[1]。

藉由比較對策前後的環境振動程度，來確認對策是否達到了預防和隔離的效果。使用石英加速度感測器M-A352可以輕鬆、快速地進行環境振動數位量測。



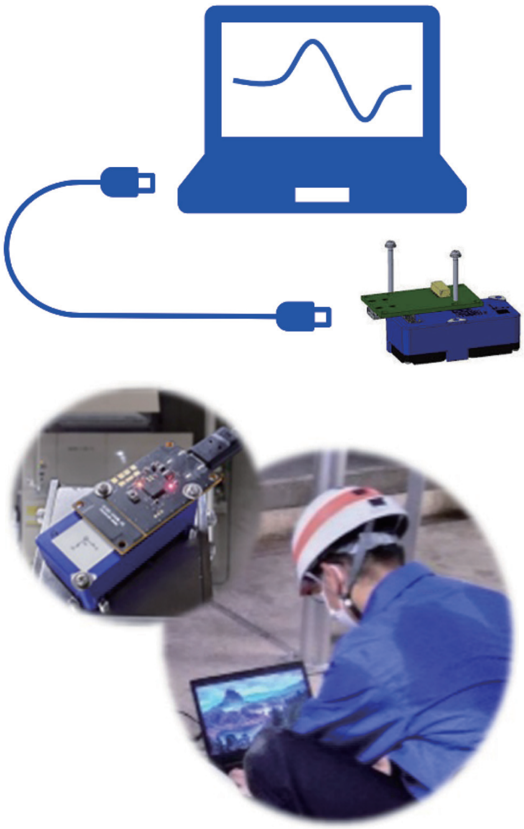
▲ 圖3　M-A352 外觀



▲ 圖4　感測值數位輸出

1. 石英振盪加速度規M-A352

M-A352 是一種高性能三軸石英振盪加速度感測器，其動態範圍表現可達±15 g，以及0.5 μg/$\sqrt{\text{Hz}}$低噪音，高解析度輸出可達0.06μg/LSB (示於圖3)。M-A352相較於傳統加速度規，具備優越的性能，係藉由採用共振頻移傳感器(resonant frequency shifttransducers)，並使用我們的微機電技術 (Micro-Electromechanical Systems, MEMS)以及感應量直接數位轉換技術製造而成 (圖4)。本感測器具備能夠抵抗外在干擾，且不需要昂貴且不易管理的類比轉換器。 M-A352在數位訊號處理過程上具有競爭力，提供便利的環境振動數位量測(圖5)。



▲ 圖5　便利的環境數位訊號量測

superior features to conventional sensors by employing resonant frequency shift transducers fabricated by our quartz MEMS technology and a direct digital conversion technique of the sensing volume (Figure 4). The sensor is resistant to external noise and does not require an expensive or difficult-to-manage analog conversion devices. The M-A352 is compatible with digital processing, providing compact and easy to use environmental vibration digital measurement (Figure 5).

A measurement system capable of measuring under VC-G class environmental vibration can simply be realized with the M-A352. VC-G level is the quiet environmental vibration that is impossible to measure with the commonly used Si-MEMS accelerometer, and is difficult to measure even with an analog servo accelerometer. The M-A352 has a metal case, which provides improved shielding against EM noises, robustness, and mounting accuracy compared to our previous models. Since the M-A352 can measure minute displacement angles, long-period vibration, and displacement, it can be applicable not only for environmental vibration measurement, but also for applications that require highly accurate data, such as structural health monitoring and predictive maintenance, as well as a variety of applications that have been difficult to apply high-precision measurement.

4.2 Applications of Environmental Vibration Digital Measurement

4.2.1 Example 1：Pre-installation measurement of equipment and evaluation of vibration isolators

In order to ensure stable production, environmental vibrations must be kept within the equipment's vibration standards. Prior to installation of the precision equipment, a location with the lowest possible environmental vibration impact can be identified with the M-A352. Environmental vibration measurements can also be used to analyze low-frequency vibrations and micro-vibrations after the installation of a vibration isolation mechanism.

4.2.2 Example 2：Assessment of the effects of walking and carting in a factory

In a factory where precision production equipment is installed, vibrations caused by the movement of people and carts may have an unexpected effect on the equipment. It is possible to determine the optimal pathway, traffic restrictions, and the selection of the trolley by an assessment of the effects of vibration.

4.2.3 Example 3：Identification of noise sources and effects on precision equipment

The M-A352 can be used to identify the source of vibration and to confirm the effectiveness of soundproofing and sound insulation measures. Sound vibrations propagating to precision equipment (such as a white interferometer, etc.), which is sensitive to the sound of campus broadcasting, can be identified. The M-A352 can also be used to investigate the source of resonant noise in reinforced concrete buildings and to take

VC-G等級的環境振動標準的量測系統，可以透過M-A352來實現。VC-G等級的安靜環境，不太可能用矽基微機電加速度規(Si-MEMS accelerometer)達到，即使採用類比伺服系統。M-A352的金屬外殼，使它能夠阻隔外在的電磁波 (Electromagnetic, EM) 干擾，相較於傳統的加速度規，其更加堅實與精確。 由於M-A352可以量測到分級的位移角、長週期振動以及位移，使它能夠應用於不只在環境振動量測，也可用於高精度的振動應用，像是結構物健康監測(Structural Health Monitoring, SHM)、預測性維護(Predictive Maintenance,PDM)以及各種的精密量測應用。

2.環境震動數位量測之應用

(1) 範例1：儀器裝設前之振動量測及隔振機構之檢核

為了確保穩定生產環境，需將環境振動維持在設備振動標準之內，裝設儀器前，可透過M-A352率先定位出適合安裝儀器的場域，也可運用於分析低頻振動以及微振，做為隔振機構之驗證。

(2) 範例2：工廠中人員走動及運輸的振動評估

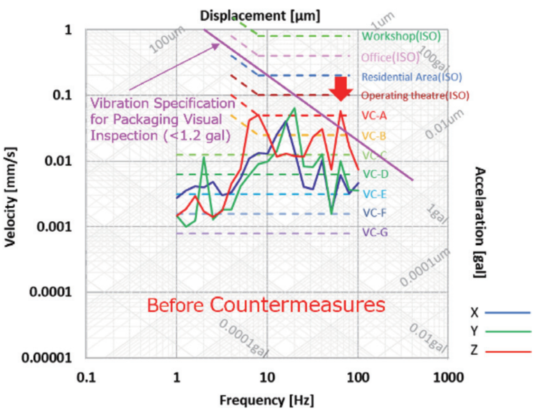
精密儀器的裝設地點，可能受到人員走動以及運輸所造成的意料外的振動影響。並藉由量測振動影響，來盡可能的優化路線。

(3) 範例3：識別振動源及其對於精密儀器之影響

M-A352可以用來識別振動源以及確認隔振效果，例如聲音振動的傳遞，對於精密儀器(像是白光干涉儀等)這種對園區廣播敏感的儀器可能會產生干擾。M-A352也可以用於調查鋼筋混凝土結構中的共振源，以防範可能的損傷情況。

(4) 內部案例分析：環境振動數位量測案例

圖6展示環境振動數位量測案例，係應用於半導體廠房，目的為消除致使半導體視覺檢查系統的故障原因，視覺檢查系統的振動規格需低於1.2 gal於各頻率區間，我們找出在部分案例中，振動大小超出此規格（圖6左側）。 以細密的量測來調查振動源，找出當熱循環測試系統運作時，相鄰的視覺檢查系統，縱向振動於63Hz超出容許振動規格。為了降低熱循環測試系統，於該區域造成的振動影響，採用了減振架於設備及樓板中間。我們也透過振動的量測，找出了最佳的儀器裝設位置，設施的規劃也跟著改變。因此63Hz的振動影響，由於以上的改善，已降低至容許振動規格內（圖6右側）。並不需要昂貴的工程，就能使故障率由原本的3.6%降低至0%。



▲ 圖6　環境振動數位量測三分圖(設施規劃改變的前後比較)

measures to prevent it.

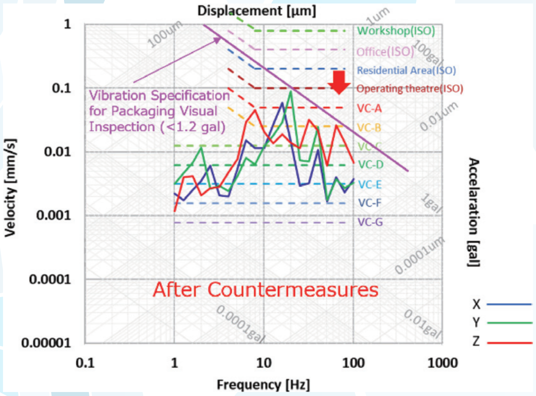
4.2.4 Internal Case Study：Example of Environmental Vibration Digital Measurement

Figure 6 shows an example of the environmental vibration digital measurement that was performed to eliminate the causes of malfunctions with a semiconductor package visual inspection system in our semiconductor factory. The vibration specification for the visual inspection system that was provided by the manufacturer should be under 1.2 gal for the entire frequency range. We measured the environmental vibrations and found that the floor vibration level exceeded 1.2 gal in some cases (Figure 6 on the left). Careful measurements were taken to identify the source of the vibration and found that the longitudinal vibration at 63 Hz exceeded the vibration specification when a heat cycle test system next to the visual inspection system was in operation. To reduce the effects of vibration of the heat cycle test system in the area, anti-vibration mounts were inserted between its feet and the floor. We also conducted the environmental vibration digital measurement to identify the location where it was least affected by the vibration from the heat cycle test system, and the facility layout was changed accordingly. As a result, the vibration at 63 Hz affecting the visual inspection system was reduced below the vibration specification (Figure 6 on the right). The failure rate due to the vibration was drastically reduced from 3.6% to 0.0% without costly floor work.

5. Conclusion

In this paper, tripartite graphs, octave analysis, and VC curves as analysis tools necessary for the identification of vibration sources and the vibration analysis, environmental vibration digital measurement are introduced. It is shown that a compact and simple vibration measurement can be realized by using the quartz crystal accelerometer M-A352. A concrete example of applications of the vibration measurement was also provided.

If a problem occurs on the worksite, countermeasures must be taken quickly and in line with the current conditions. When a problem is caused by environmental vibration, it may be hard to notice. Even if it is noticed, it may be difficult and troubling to deal with, since it may not be your field of expertise. We hope that this paper will help you to take prompt and effective measures against vibration problems.



▲ 圖6　環境振動數位量測三分圖(設施規劃改變的前後比較)（續）

五、結語

本文中，介紹了三分圖、八音頻帶以及振動標準線，這些為識別振動源、振動分析以及振動量數位測的必要工具。振動量測應用範例也證實了，石英振盪加速度規M-A352之小巧及便利的振動量測能力。

如果工作場域發生振動相關問題，因地制宜的對策就必需迅速的採用；若此問題源於環境振動，它則難以被察覺；即使它被察覺了，也不容易處理，因為這可能不是在你的專業領域內。我們希望本文可以幫助你採取即時且有效的量測來解決振動問題。

✉ 參考文獻

[1] Akira Teramura、Measures to reduce micro-vibration and its simulation、Noise Control Engineering、Vol.10 No.2、pp. 80-84、1986 (Japanese).

[2] International Organization for Standardization: Acoustics - Preferred frequencies, ISO 266, 1997.

[3] International Electrotechnical Commission: Electroacoustics - Octave-band and fractional-octave-band filters - Part 1: Specifications, IEC 61260-1,2014.

[4] Colin G. Gordon, “Generic Vibration Criteria for Vibration-Sensitive Equipment”, Proc. SPIE 1619, 1991.

[5] International Organization for Standardization: Mechanical vibration and shock - Evaluation ofhuman exposure to whole-body vibration - Part 1:General requirements, ISO 2631-1, 1997.

[6] International Organization for Standardization:Mechanical vibration and shock - Evaluation ofhuman exposure to whole-body vibration - Part 2:Vibration in buildings (1 Hz to 80 Hz), ISO 2631-2,2003.

[7] Hal Amick, Michael Gendreau, Todd Busch, and Colin Gordon, “Evolving criteria for research facilities: vibration”, Proc. SPIE 5933, Buildings for Nanoscale Research and Beyond, 2005.