Precision Metrology 6 –Thermal Errors

III. Thermal error or thermally induced errors

:Error due to temperature change of the machine element by the heat sources

Heat sources:

motors, control electronics, bearings, transmission, hydraulic oil, gears/clutch, pumps and engine, guideways, process, chips, coolant system, lubricating systems, external/environmental heats, operator (human)

3 Heat transfer paths:

①Conduction(ambient or vacuum)

: Energy transfer from the high temperature region to low temperature region, when there exists temperature gradient in a body.

$q=kA\cdot\partial T/\partial x$, k=thermal conductivity

Materials with thermal-conductivity(W/m°C)

Copper	385	Al	202	Iron 73
Steel	43	Marble	2.5	Glass 0.78
Water	0.556	Air	0.024	

②Convection(ambient)

:Heat transfer at the wall of temperature gradient

$q=hA(T_w-T_\infty)$, where h=convection coefficient

T_w and T_∞ are temp. at the wall and free stream

Convection coefficient for modes, [W/m^2K]

4.5 for free convection

12 for forced convection of 2m/s flow

75 for forced convection of 35m/s flow

③Radiation(ambient and vacuum)

:electro-magnetic radiation due to temperature difference

$q=F_eF_G\sigma A(T_1^4-T_2^4)$;

F_e=emissivity, F_G=view factor

σ=Stefan-Boltzmann Constant=5.669E-8 [W/m^2K^4]

Various Temperature fields:

1)Uniform temperature field other than 20°C, or 68°F

; uniform indicates, $\partial/\partial x \doteqdot \partial/\partial y \doteqdot \partial/\partial z \doteqdot 0$

2)Temperature gradient field (static effects)

; $\partial/\partial x \neq 0$ or $\partial/\partial y \neq 0$ or $\partial/\partial z \neq 0$, but $\partial/\partial t \doteqdot 0$,

3)Dynamic temperature variation field (dynamic effects)

; $\partial/\partial t \neq 0$

Affected structure

:Machine Frame, Master (Screw or Scale), Workpiece

Thermal error components

:Total error = Size error + Form error

Size error= error due to elongation or contraction such as length, diametre

Form error(or profile error)=deviational error from the profile or form, straightness/flatness error change due to the guideway deformation

Thermal expansion coefficients (unit: ppm/K)

Al	23.03	Fe	12.3	Ti	8.35
Cu	16.5	Ni	13.3	Zn	25
Sn	21.2	Co	13.3	Cr	6.2
Ag	19.2	Au	14.15	Pt	9
Quartz	0.55	Glass	3.78	SiC	4.4
Carbon	0.7~6	Al_2O_3	8	SiO_2	8.8
SUS304	17.3	SUS316	16	Zerodour	0
Invar	1~2				

Thermal error measurement

①Device for Measurement

-Displacement measurement

:Length measurement sensors such as LVDT(Linear variable differential transducer), Capacitive sensor, Micrometer, Vernier, Dial Gauge, laser interferometer, etc.)

-Temperature measurement

:Thermo-couple, thermistor, pyrometer, surface contact sensor

-Temperature distribution: Infra-red camera

②Guidelines

-Drift test for sensors during long term such as 24h

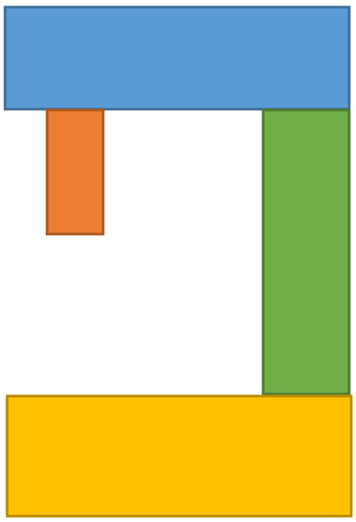
: Resistors, Capacitors give always variation or 'drift' during the temperature change

-Low thermal expansion coefficients material for

Jig/Fixture

:Invar (≒1/10 of steel), and Zerodour(≒0)

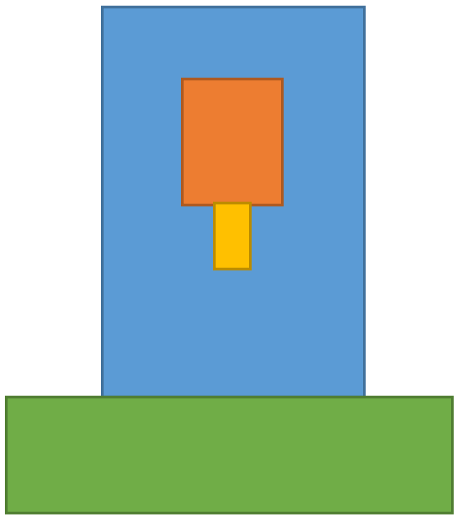
③Observations



Unsymmetrical

('C' shape)

Large Thermal Error



Symmetrical

Small Thermal Error

∴ Better Design

In practical application,

-Temperature control (by cooling system for spindle bearing, oil, coolant tank); cold air blowing; thermal enclosure; periodic resetting,

-Thermal error compensation for spindle growth and tilt, axial growth and deformation via controller, based on thermal error modeling

The following is a typical example for the spindle thermal error measurement and modeling:

[Source: ‘Thermal Error Measurement and Real Time Compensation System for the CNC Machine Tools Incorporating the Spindle Thermal Error and the Feed Axis Thermal Error’, H.J. Pahk, S.W. Lee, International Journal of Advanced Manufacturing Technology, 20(7), 487-494, 2002]

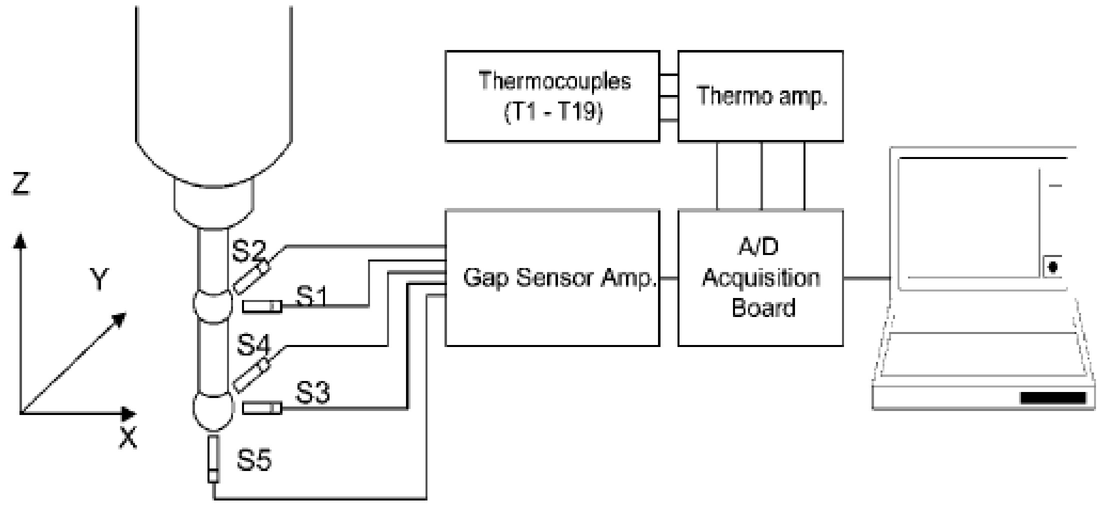


Fig. 1. Sensors for measuring spindle drift errors.

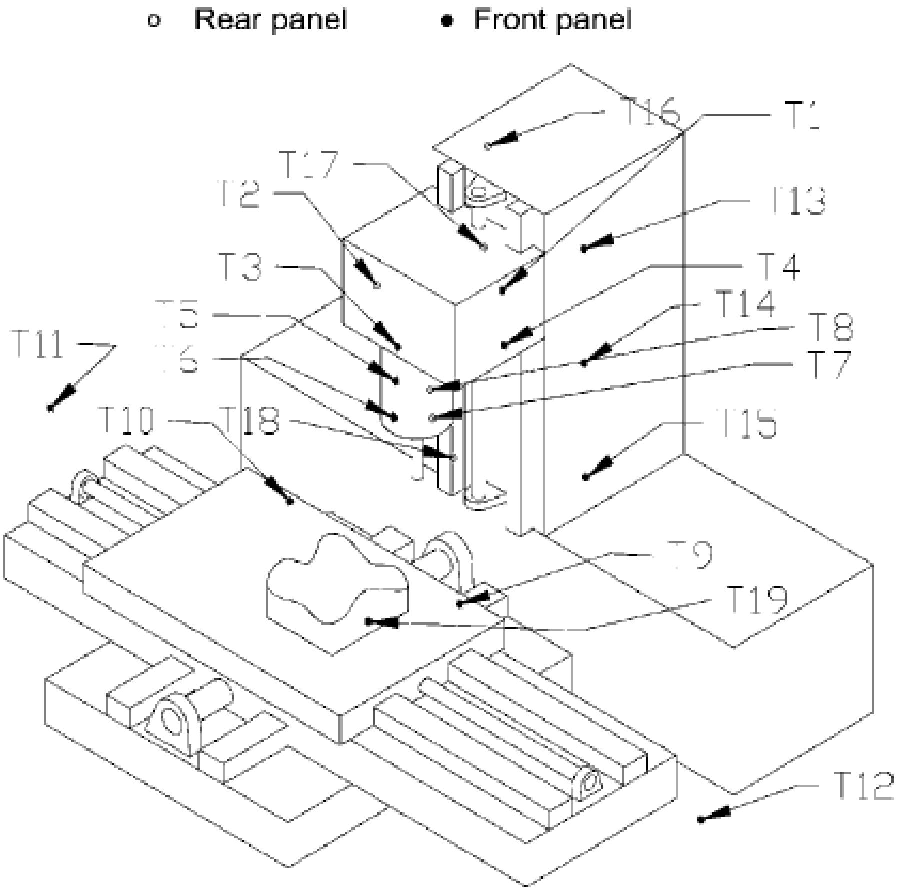


Fig. 2. Thermal sensor location.

IV. Environmental Error

(1) Environmental Change in Temperature

Ambient temperature change is very sensitive to the accuracy of machines, is directly linked to the thermal deformation of the machine elements, that is 12 ppm/K for steel parts, 24 ppm/K for aluminum parts.

Few °C change in temperature is very common, thus few 10um change or drift is typically observed in X, Y, Z directions, especially in unsymmetrical structure (‘C’ frame), although the short time repeatability keeping very high.

Typical causes of temperature change: day and night, shifting period, before and after break time.

How to solve->

-Strict control/monitor for the temperature of clean room, air inlet/outlet to machines,

-LECC(Local Environmental Control Cell) or thermal enclosure

-Thermal error compensation by software, together with temperature measurement.

-Machine operation after temperature saturation, this is effective when the heat capacity of affected element is quite low such as in Glass.

Heat capacity=mass· specific heat=mc

specific heat=Heat required for 1g mass to raise 1°C, unit [J/Kg°C]

Al	900	Cu	387	Fe	448
Glass	837	Granite	860	Water	4186

Ex) Just processed glass is still in high temperature, but it cools down after short period in contact with glass chuck of machine, as the heat capacity of glass is very low, while the chuck is of quite large heat capacity.(and temperature is controlled via air inlet/outlet through the chucking holes.)

(2) Floor Vibration

No machines are free from the floor vibration.

Floor vibration transmits to machine base, to machine structure, to work table, to carriage, and to tool tip/probe. This transmitted vibration makes relative motion between the probe and the workpiece, lowering the repeatability very much. Range of less than few 10 nm repeatability(3σ) cannot be achieved without proper vibration isolation. For precision manufacturing environment, there are Vibration Criteria such as VC-A, VC-B, VC-C, VC-D, and VC-E, at every 6dB difference interval.

①Vibration Isolation: to isolate the vibration from the source or to suppress the transmissibility during the transmission.

$dB \equiv 20Log_{10}|H_2/H_1|$, where $|H_2/H_1|$ is the transmissibility; and H_1 is the amplitude of the source vibration, H_2 is the amplitude of transmitted.

$|H_2/H_1|=10^{-3/20}$ = 0.7 @ -3 dB

$|H_2/H_1|=10^{-6/20}$ = 0.5 @ -6 dB

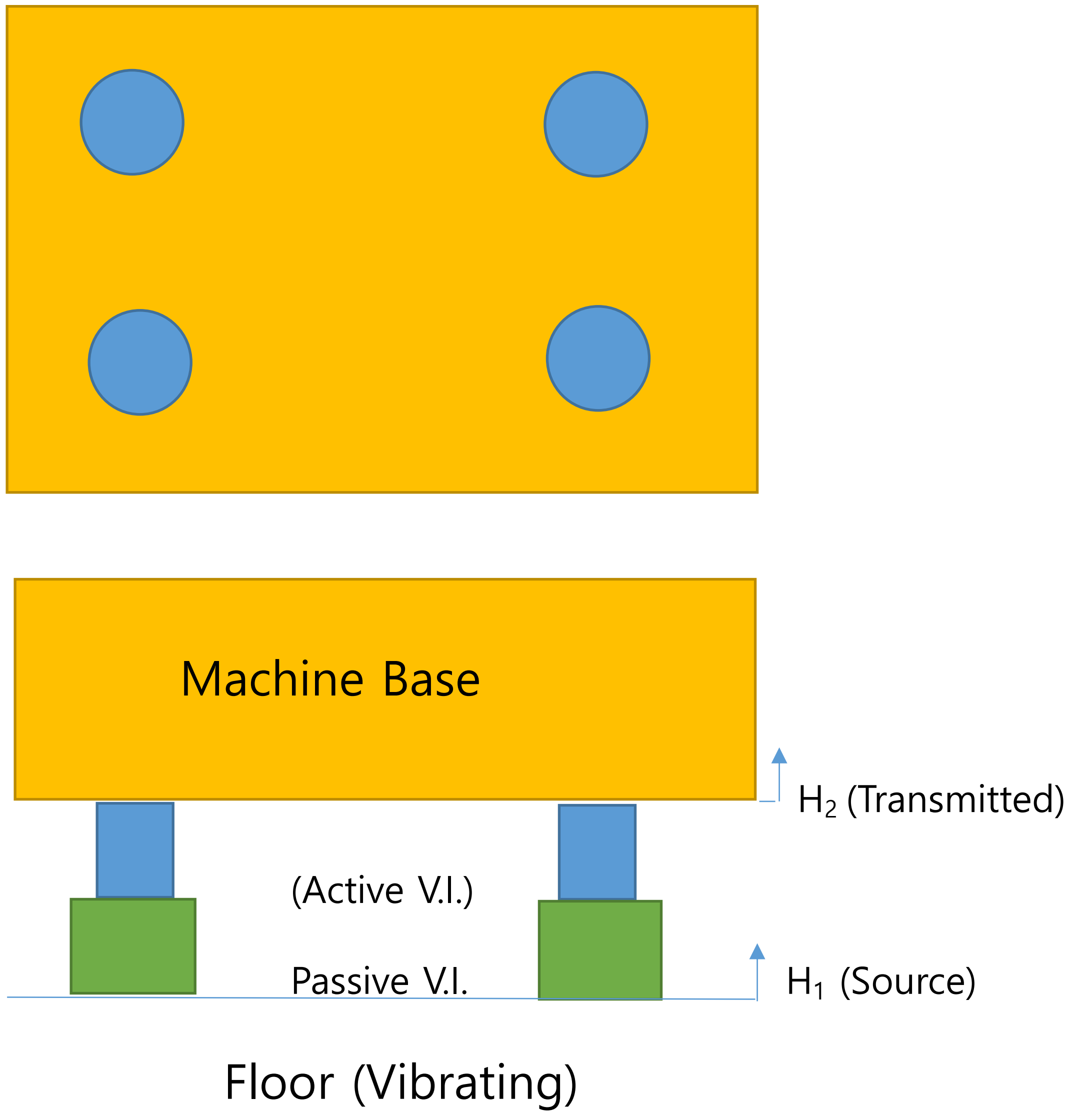
$|H_2/H_1|=10^{-20/20}$ = 0.1 @ -20 dB

Two types of vibration isolation

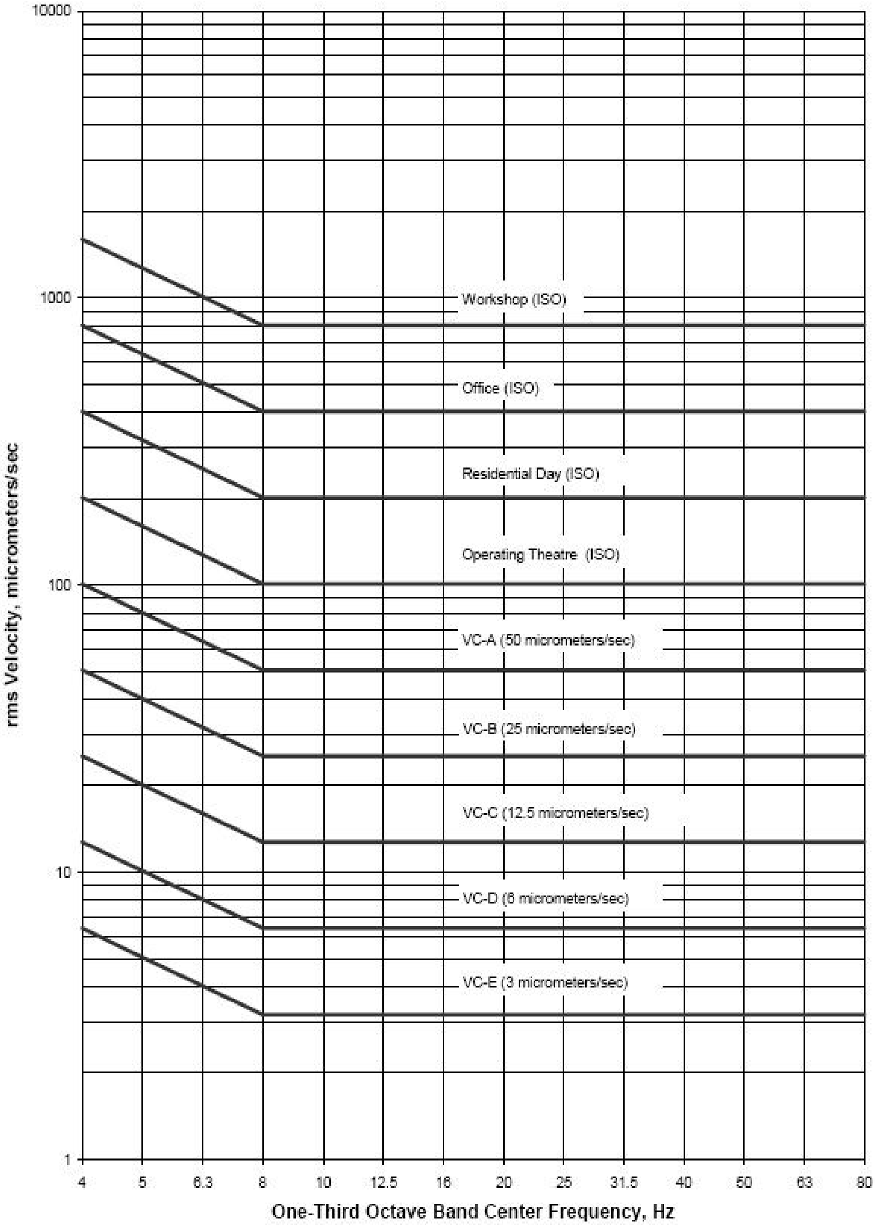
Passive Vibration Isolation: It is to isolate passively; it is to reduce the transmissibility via using passive elements such as pneumatic cylinders, rubber, dampers, etc. The performance of -20dB is a typical target of high performance commercial pneumatic isolators.

Active Vibration Isolation: It is to isolate actively; it is to superpose the complimentary vibratory motion to the residual vibration, via adapting actuators such as electromagnetic actuators, piezo actuators, etc. This is to isolate vibration at low frequency range around less than 20Hz range, typically.

Also, -20dB is a typical target.



Machine Base
H2 (Transmitted)
(Active V.I.)
Passive V.I.
H1 (Source)
Floor (Vibrating)

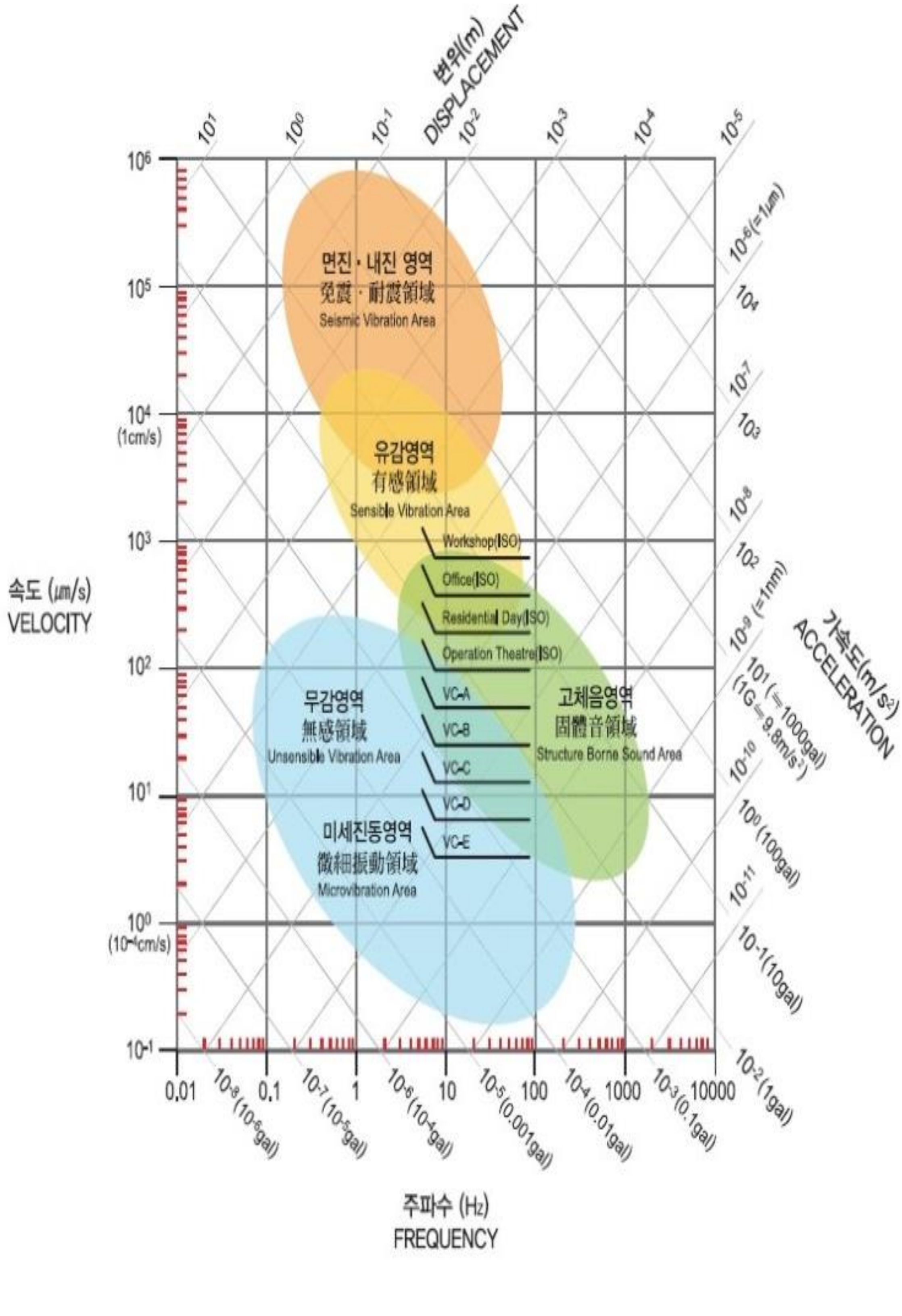


10000
1000
100
10
1
rms Velocity, micrometers/sec
Workshop (ISO)
Office (ISO)
Residential Day (ISO)
Operating Theatre (ISO)
VC-A (50 micrometers/sec)
VC-B (25 micrometers/sec)
VC-C (12.5 micrometers/sec)
VC-D (6 micrometers/sec)
VC-E (3 micrometers/sec)
4
5
6.3
8
10
12.5
16
20
25
31.5
40
50
63
80
One-Third Octave Band Center Frequency, Hz

Criterion Curve	Max Level micrmeters/sec ,rms (dB)	Detail Size, microns	Description of Use
Workshop (ISO)	800 (90)	N/A	Distinctly felt vibration. Appropriate to workshops and non-sensitive areas.
Office (ISO)	400 (84)	N/A	Felt vibration. Appropriate to offices and non-sensitive areas
Residential Day (ISO)	200 (74)	75	Barely felt vibration. Appropriate to sleep areas in most instances. Probably adequate for computer equipment, probe test equipment and lower-power (to 20X) microscopes.
Op. Theatre (ISO)	100 (72)	25	Vibration not felt. Suitable for sensitive sleep areas. Suitable in most instances for microscopes to 100X and for other equipment of low sensitivity.
VC-A	50 (66)	**8**	Adequate in most instances for optical microscopes to 400X, microbalances, optical balances, proximity and projection aligners, etc.
VC-B	25 (60)	**3**	An appropriate standard for optical microscopes to 1000X, inspection and lithography equipment (including steppers) to 3 micron line-widths.
VC-C	12.5 (54)	**1**	A good standard for most lithography and inspection equipment to 1 micron detail size.
VC-D	6 (48)	**0.3**	Suitable in most instances for the most demanding equipment including electron microscopes (TEMs and SEMs) and E-Beam systems, operation to the limits of their capacity.
VC-E	3 (42)	**0.1**	A difficult criterion to achieve in most instances. Assumed to be adequate for the most demanding of sensitive systems including long path, laser-based, small target systems and other systems.

(where, 1 gal=1 cm / s^2

1G= 9.8m/ s^2=980 cm/ s^2≒1000 gal)



변위(m)
DISPLACEMENT
면진·내진 영역
免震·耐震領域
Seismic Vibration Area
유감영역
有感領域
Sensible Vibration Area
Workshop(ISO)
Office(ISO)
Residential Day(ISO)
Operation Theatre(ISO)
VC-A
VC-B
VC-C
VC-D
VC-E
무감영역
無感領域
Unsensible Vibration Area
미세진동영역
微細振動領域
Microvibration Area
고체음영역
固體音領域
Structure Borne Sound Area
속도 (μm/s)
VELOCITY
(1cm/s)
(10-4cm/s)
가속도(m/s2)
ACCELERATION
10-6(=1μm)
10-9(=1nm)
(1G≒9.8m/s2)
101(≒1000gal)
100(100gal)
10-1(10gal)
10-2(1gal)
10-3(0.1gal)
10-4(0.01gal)
10-5(0.001gal)
10-6(10-4gal)
10-7(10-5gal)
10-8(10-6gal)
0.01
0.1
1
10
100
1000
10000
주파수 (Hz)
FREQUENCY

일반 진동 규제치 • General Vibration Criteria, BBN-Criterion

Description / Class	Facility Equipment or Use	Vibration Criteria	
		4~8 [Hz] RMS Acceleration	8~80[Hz] RMS Velocity
일반적인 진동환경	일반사업장	4gal (변위16μm)	800μm/s
	사무실	2gal (변위 8μm)	400μm/s
	거주지 및 Computer System	1gal (변위 4μm)	200μm/s
	100× 현미경, 로봇수술실, Operation Room, 일반연구실 기타	0.5gal (변위 2μm)	100μm/s
정밀진동 Class : A	400×현미경, 측정실 Optical or Other Balance Optical Comparators, 전자장비, 생산설비 등 ※검사, Probe Test, 생산 지원설비 및 장치	0.25gal (변위 1μm)	50μm/s
정밀진동 Class : B	400× 이상 현미경, 精密안과, 신경계 수술실, 防振설비를 갖춘 광학장비, 반도체 생산설비 등 ※Aligner, Steppers등 3μm이상 선폭 노광장치	0.13gal (변위 0.5μm)	25μm/s
정밀진동 Class : C	30000× 전자현미경, Magnetic Resonance Imager, 반도체 생산설비 ※ Aligner, Steppers등 1μm 선폭 노광장치 → 1M DRAM정도	0.06gal (변위 0.25μm)	12μm/s
정밀진동 Class : D	30000×이상 전자현미경, Mass Spectrometer, 세포이식 장치, 반도체 생산설비 ※ Aligner, Steppers등 0.5μm선폭 노광장치 → 4M DRAM 정도	0.03gal (변위 0.12μm)	6μm/s
정밀진동 Class : E	Unisolated Laser and Optical Research System, 반도체 생산설비 ※ Aligner, Steppers등 0.25μm 선폭 노광장치 → 64M DRAM 정도	0.015gal (변위 0.06μm)	3μm/s

※ 일반적인 정밀장비의 정밀도, 분해능에 따른 바닥의 허용진동기준임.

Source:http://blog.naver.com/lee_jinhwan/50174644378

②Data measurement strategy during vibrating or noisy environment

:To use the average of multiple measurements, reducing the uncertainty by $1/\sqrt{n}$, or to apply digital filtering to remove the vibrating components, or to use model based filtering technique.

V. Software Error

Control algorithm error such as the following or overshooting error, steady state or transient error, gain tuning error, gain mismatch error.

Calculation error due to insufficient data samplings, non-recognized methods of calculation.

Number-of-digits related error due to the non-adapting of double precision format, truncation error.

Software verification, validation, or authorization are very useful methods for the reference standard of data.