ANV

MEASUREMENT SYSTEMS

CIVE

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Groundborne Noise and Vibration:- Instrumentation & Data Processing

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10 November 2020

Overview

Transducers

Mounting and Positioning of Transducers

Recording Instrumentation

Proprietary Equipment

Equipment Calibration

Transducers

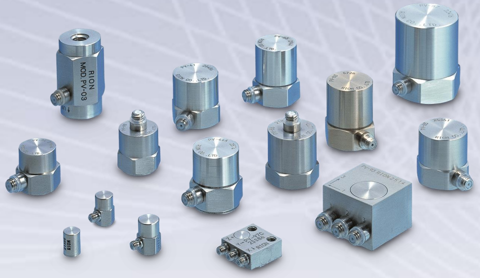
In principle can measure:

Acceleration;

Velocity; or

Displacement.

Although the book looks at a wider range of transducers this presentation will concentrate on the two types of transducer most commonly used on site:-



Accelerometers; and

Geophones.

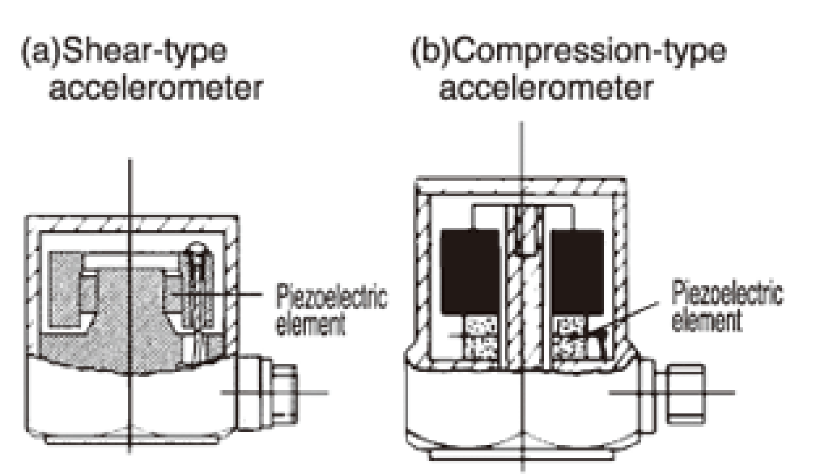
Measurement Systems

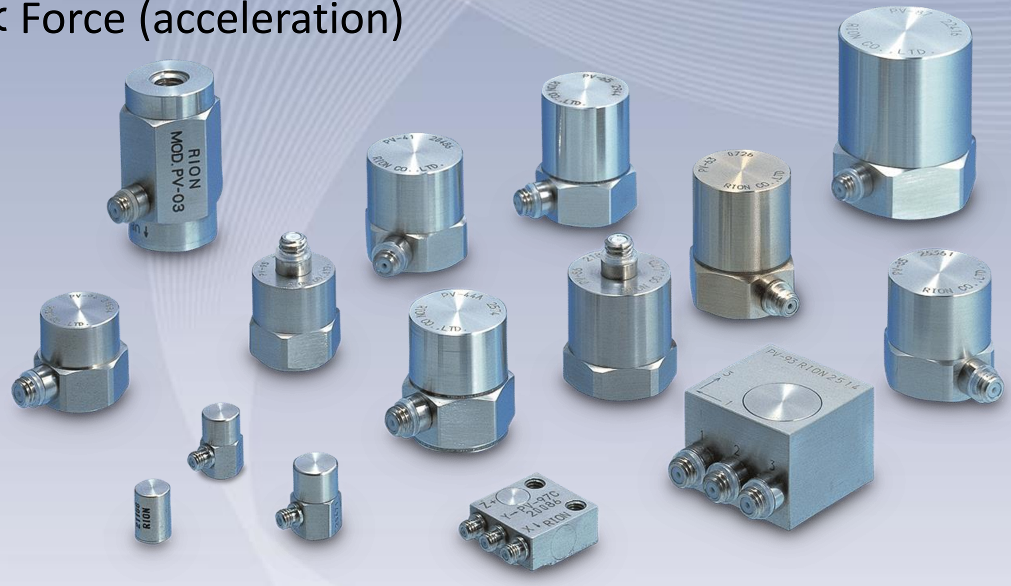
Transducers: Accelerometers

Piezoelectric type the most common

Can be single axis or tri-axial

Piezoelectric materials produce a Charge (Q coulombs) ∝ Force (acceleration)





Shear type generally more suited to groundborne noise & vibration:-

Higher Sensitivity

Lower Noise

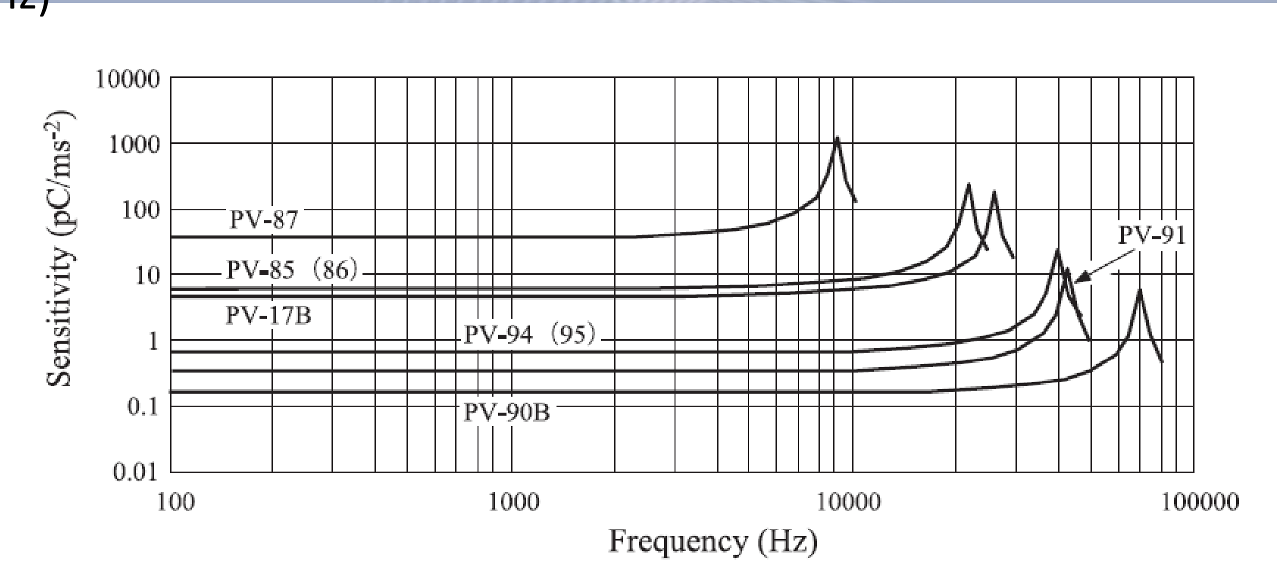
Transducers: Accelerometers

Operating range below resonant frequency (kHz)

Response below 1 Hz possible but not d.c.

Charge is not a particularly useful quantity

Charge Amplifier: Voltage ∝ Charge ∝ Acc



Many (Most?) Modern Accelerometers Incorporate a Charge Amplifier and give a direct Voltage Out

Transducers: Accelerometers

Charge Type

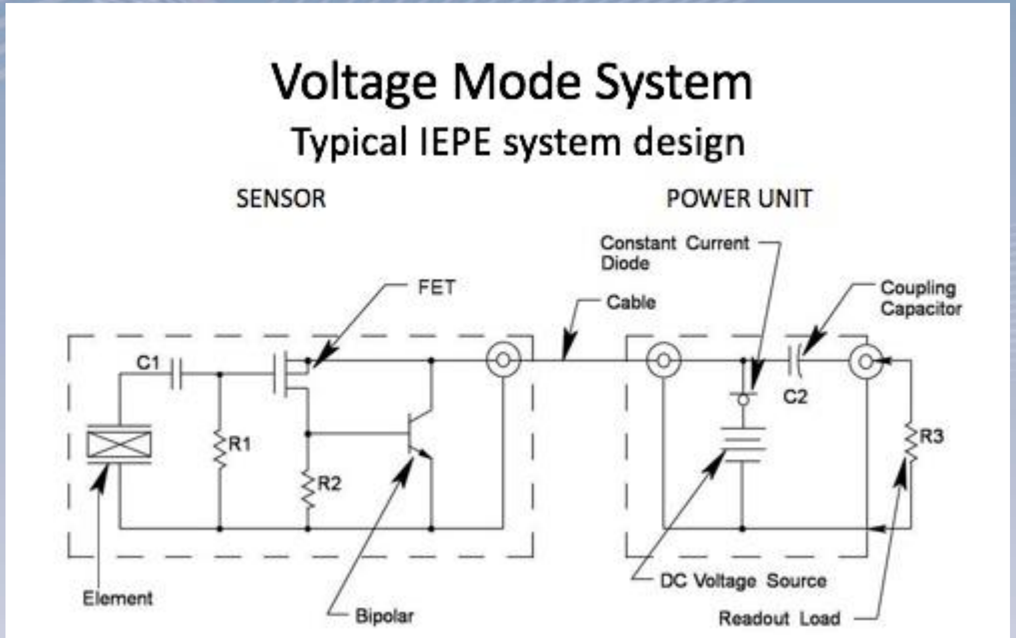
Sensitivity pC/ms^{-2} or pC/g

Need to Use with Charge Amplifier

Voltage Type (also known as CCLD, ICP, IEPE)

Sensitivity in mV/ms^{-2} or mV/g

Requires a constant current power source (typically 2 – 4 mA)



Credit: Techni Measure Website

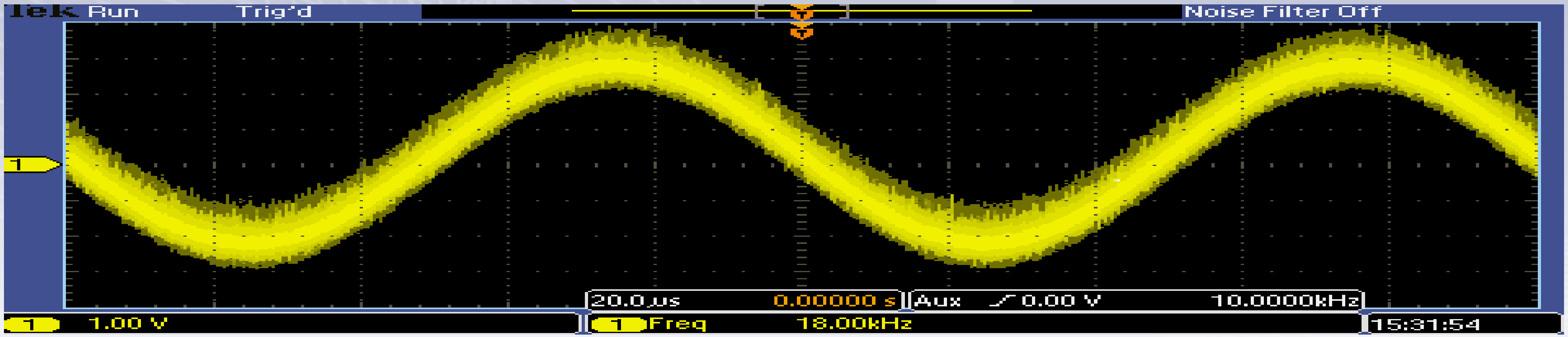
Transducers: Accelerometers

Voltage Type Accelerometers Much More Common and Convenient than Charge Type but………

Very good low frequency response (< 1 Hz) can be achieved with a charge accelerometer direct into high impedance charge amplifier which is difficult to replicate with an integrated design.

The sensitivity of a charge accelerometer is obvious from its specification. The sensitivity of a voltage Type accelerometer is made up of a combination of the sensitivity of the sensor and the gain of Integrated amplifier.

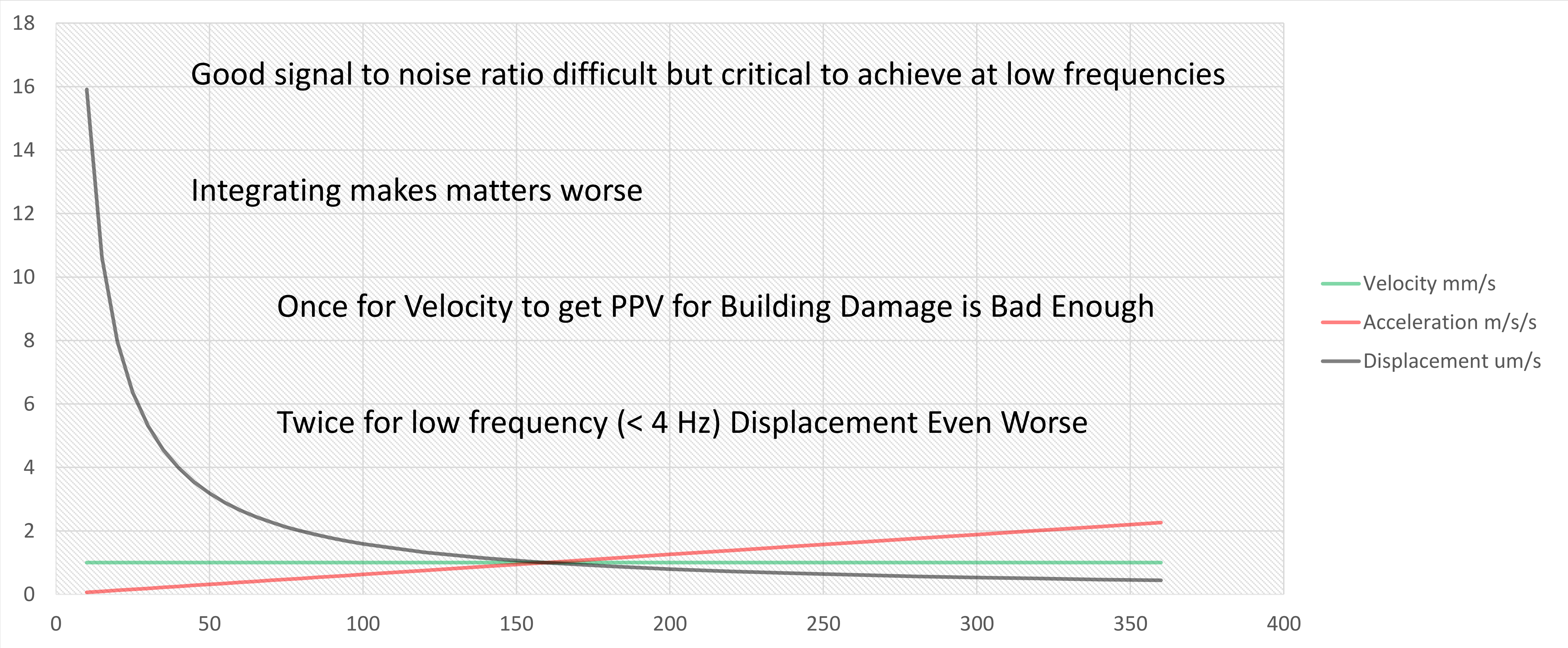
Low Sensitivity Accelerometer + High Gain Integrated Amplifier = Big but Noisy Signal



Credit: Tektronix Website

MEASUREMENT SYSTEMS

Transducers: Accelerometers



Transducers: Geophones

Suspended Coil in Magnetic Field

$V_{out} = B \times l \times u$

Voltage easy to work with

Decent signal ~ 30 mV/mms^{-1}

Passive

No requirement for power supply

Low noise

In principle, linear frequency response above *fr*

Simple, relatively low-cost device

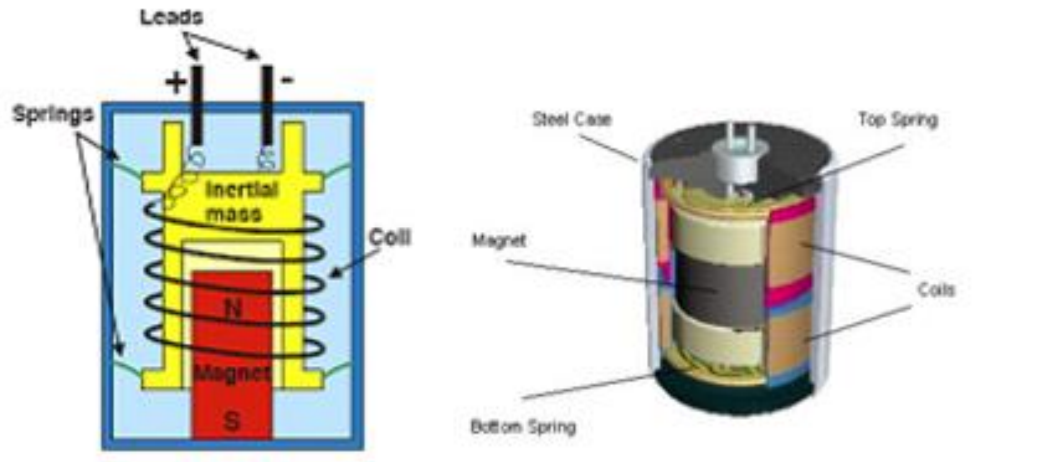
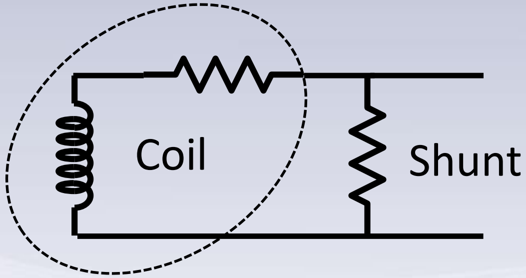


Image credit: Deutsches Elektronen-Synchrotron (DESY)



Transducers: Geophones

Without additional damping strong resonance

Typical f_r in the range 4 – 8 Hz

Shunt resistor used to achieve critical damping
by increasing electromagnetic damping (Lenz's Law)

Response -12 dB per octave below f_r

Additional Processing required for low frequencies

Very difficult to verify low frequency performance

Additional Processing will increase noise floor

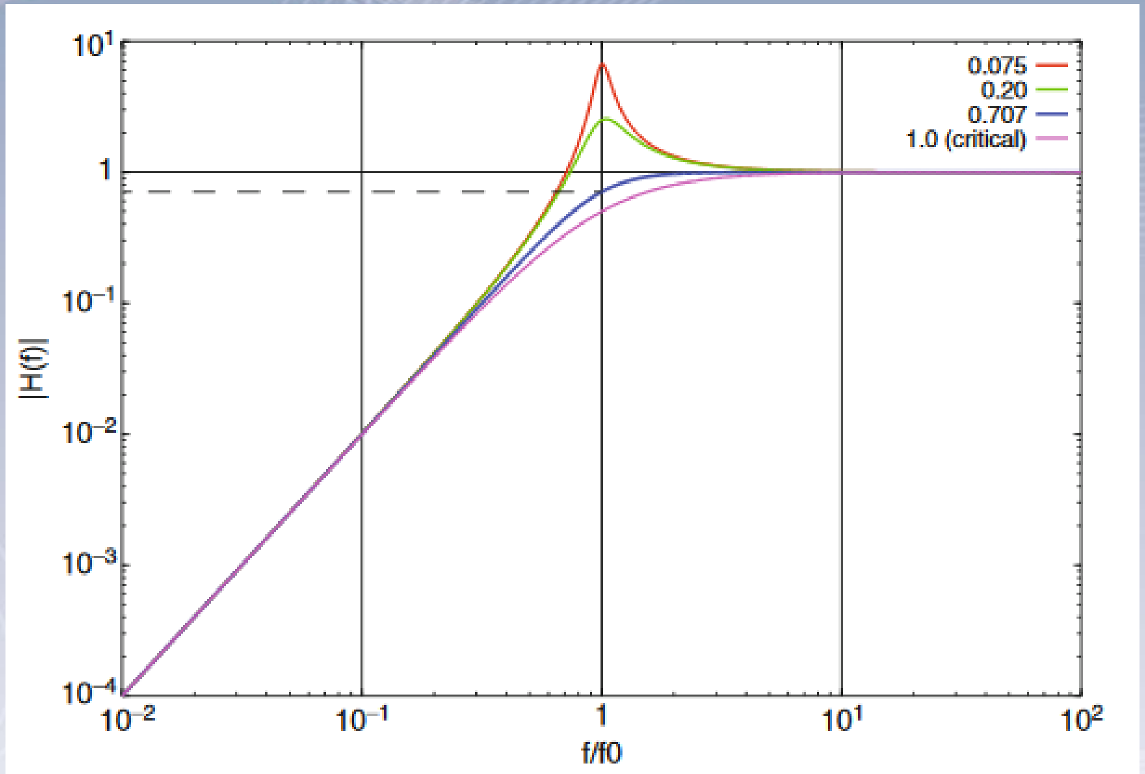


Image Credit Encyclopedia of Earthquake Engineering
DOI 10.1007/978-3-642-36197-5_174-1

Transducers: Geophones

Some Further Considerations

Must be used in correct plane

Output affected if not correctly orientated

Range at low frequency limited by maximum Excursion of geophone

Low cost devices' quality can be an issue

Coil suspension may not be linear affecting

Amplitude linearity

Frequency Response

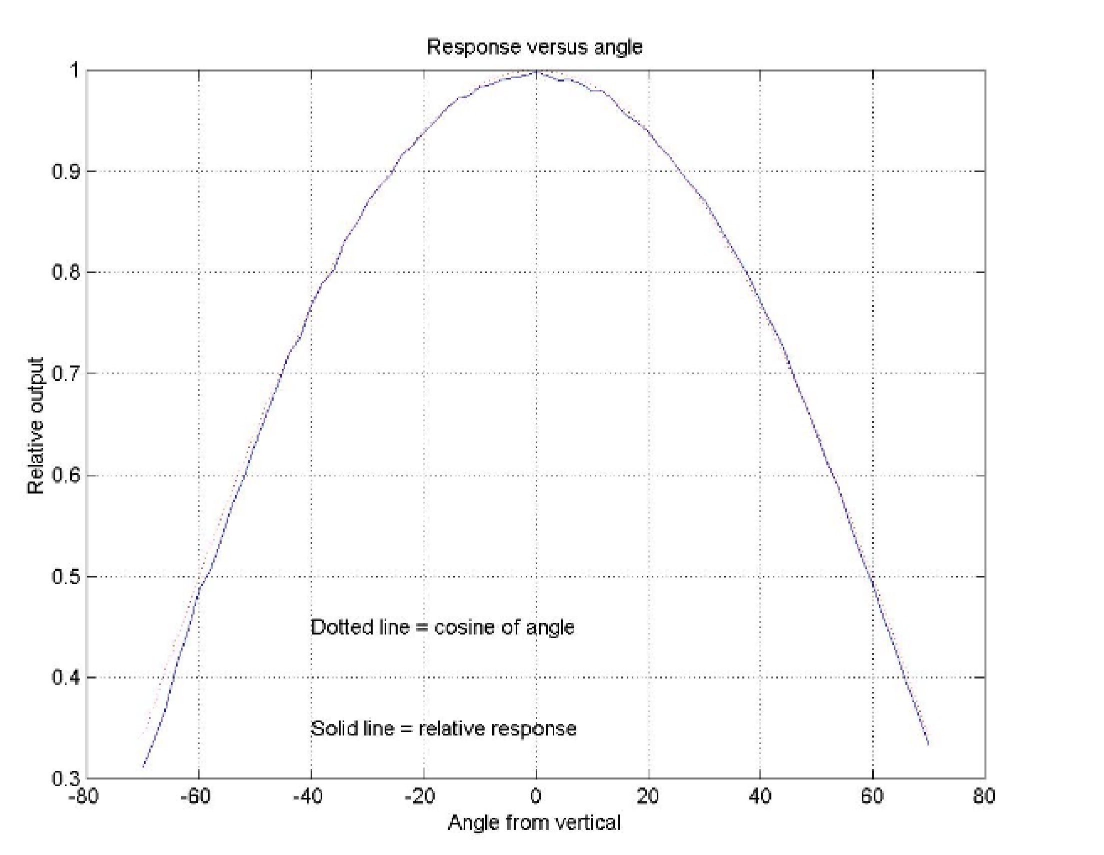


Image Credit *Bertram, Gallant, and Stewart*
CREWES Research Report — Volume 11 (1999)

Transducers: Geophones or Accelerometers?

In reality neither ideal

But neither terrible if used well

4.5 or 8 Hz geophones common

- Good quality systems (near) critically damped
- Ouput processed to counteract -12 dB/octave < f_r
- S/N increasingly a factor with lower amplitude & frequency

Good quality big accelerometers

- Workable signals down to 0.5 Hz
- S/N increasingly a factor with lower amplitude & frequency
- Potentially exacerbated by need for single (velocity) and double (displacement) integration

Transducers: Geophones or Accelerometers?

Do the mostly low frequency issues that affect both Accelerometers & geophones lead to problems practically?

Very low frequencies and displacement important for Building Damage.

But levels associated with damage very high so S/N of limited concern

w_b weighting suggests that sensitivity for perceptible vibration decreases quite quickly below ~ 5 Hz

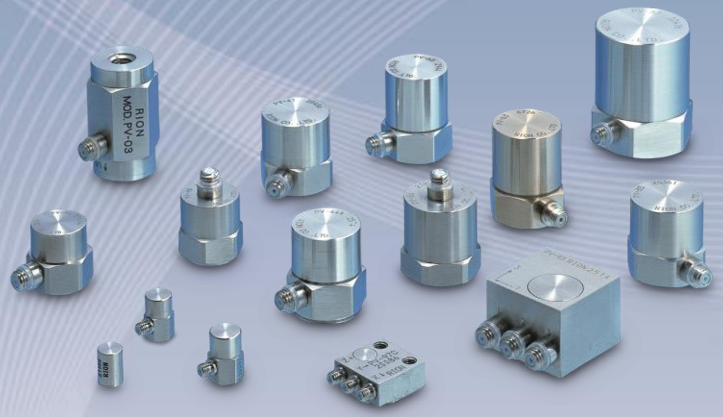
But in order to demonstrate compliance with BS 6472:1 It is necessary to measure down to 0.5 Hz

Transducers: Geophones or Accelerometers?

Can you carry out a BS 6472: 1 assessment with geophones?

Instrumentation requirements in BS EN ISO 8041:2017

Amplitude and phase requirements set out for acceleration-based systems



Standard states that velocity-based instruments can be used "provided the overall requirements are satisfied"

So in principle yes, but:-

- Converting the acceleration based design parameters to velocity v. difficult
- Achieving the overall requirements potentially difficult partially because The dynamic behaviour of geophones is very different to accelerometers

BS 5228: 2 simply states that measurements of weighted acceleration or VDV should be carried out using accelerometers.

Mounting and Positioning of Transducers

General Principles

Transducer rigidly coupled to the structure/surface/medium of interest

Due consideration to be applied to:-

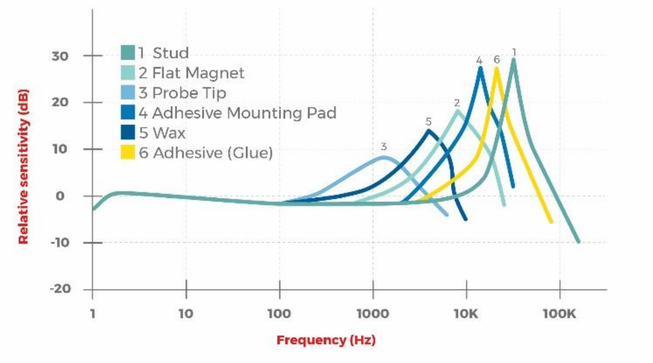


Image Credit: Vibration Research Website

Response of the connecting structure (e.g. ground spike, wall bracket)

Response of the transducer mounted on the connecting structure

The potential for the mounted transducer to affect the dynamics of the structure/surface/medium of interest

Mounting and Positioning of Transducers

Measurements to Assess the Risk of Damage to Existing Structures

BS EN ISO 4866: 2010 is the principal UK reference

Best Position – at the base of the building/structure on the side facing the source of vibration

Second best – on an external wall facing vibration source; or
- on the ground floor adjacent to an external wall facing the vibration source

Best Fixing – transducer screwed to a stud secured by expanding fixing in hole drilled in structure

Alternatives

Transducer secured to mounting plate which is in turn screwed onto structure

Transducer glued to structure with thin layer of rigid glue

Larger/heavier transducers or transducer on plate or block placed on horizontal surface (BS EN ISO 4866 advises this is only suitable of vibration will not exceed 2 ms^{-2})

BS EN 4866 - mass of transducer + mounting < 1% of the element of the structure it's mounted on

Mounting and Positioning of Transducers

Measurements to Assess Perceptible Vibration in/on Existing Structures

Guiding principle – measure at "point of entry" – i.e. where vibration will be transmitted to people

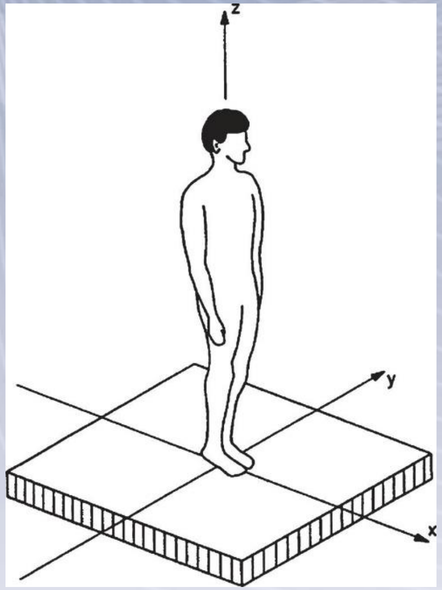


Image Credit: IOS Press

Normally sufficient to measure on the floor

Measure where you expect the vibration to be highest (e.g. centre span for wooden floors)

Best Fixing – transducer bolted/screwed to the floor (very often not acceptable)

Larger/heavier transducers or transducer on plate or block placed on horizontal surface widely used for this application where vibration magnitudes are likely to be quite low

Carpets – ideally remove all or a section of the carpet and measure on the hard floor
- if not possible spike through the carpet to floor below

Lightweight floors – consider whether loading required to be representative of occupied dynamics

Wooden floors – watch out for damaged floorboards, other defects and variation in properties

Mounting and Positioning of Transducers

Measurements in/on The Ground

- Baseline Measurements Prior to Development
  - Measure where the vibration will be transmitted to the proposed building
    - Ground Level and at a depth to reflect the lowest point of proposed building foundations
- Brownfield Sites with Existing Foundations or buried slabs
  - Mounting/Positioning as for existing structures
  - But adjust results to reflects dynamics of proposed vs. existing situation

- Sensor Mounting for Vibration on or in the ground
  - As a general principle measure on consolidated ground (not overlying or loose fill material)
  - 5 main options with variations

Mounting and Positioning of Transducers

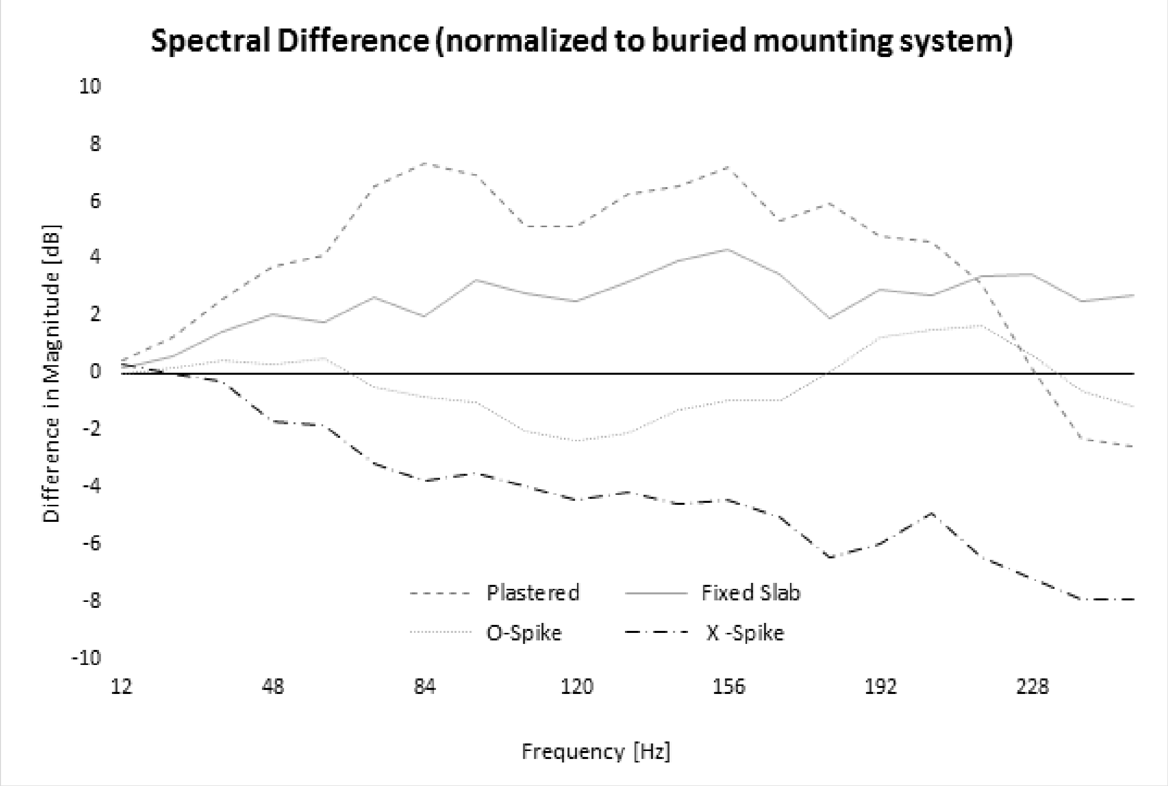
Measurements in/on The Ground: Mounting Options

Spikes	~ 30 c.m. length a good compromise (resonances vs adequate coupling)
	At least 10mm diameter required for good coupling & to resist rotation
	“L” cross-section spikes can be good but difficult to drive
Metal Plate	Partially burying the plate/transducer can improve coupling
	Must have sufficient area to provide stable mounting (avoid rocking effects)
Block/slab	Need to balance sufficient mass for coupling vs too much mass loading the ground
Cast in Place Block	Concrete, plaster of Paris or dental plaster patch in small excavation
	Transducer stud cast into the patch
	It is suggested to try and match the density of the patch with the ground
Buried Transducer	Careful attention must be applied to the orientation of the transducer
	Backfill must ensure coupling of transducer and reflect ground conditions
	Very difficult to implement with large particle size soil/ground
	Repeatability of measurements likely to prove difficult

Mounting and Positioning of Transducers

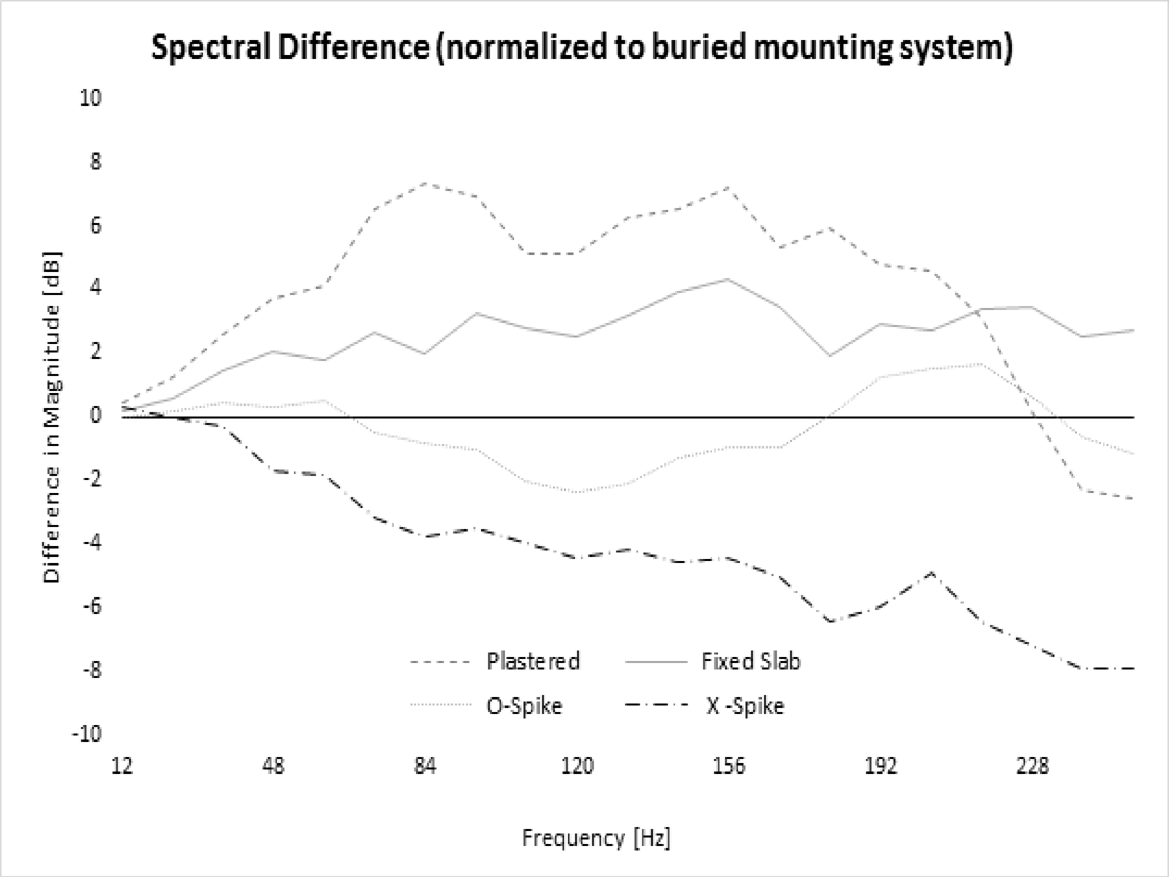
Comparison of Different Ground Mounting Options

Davilez et al. compared the vibration spectra from train passbys measured using 5 mounting methods



Mounting and Positioning of Transducers

Comparison of Different Ground Mounting Options



Plot is average data from 6 passbys

Mounting method significantly affects Frequency content

But D'Avilez et al. noted that spectra varied Greatly with both input vibration characteristics and measurement location

No general comparisons of mounting methods possible from these results

Choice of mounting technique up to individual practitioners

Best Practice:

- Clearly describe chosen method
- Explain reason for choice

Recording Instrumentation

When 1st Edition published in 2001 very little if any instrumentation from major manufacturers suited to Accurate and detailed measurement of Groundborne Vibration

Especially w.r.t. VDV and the low vibration levels associated with GBN

1st Edition Recording Instrumentation Section was almost a recipe for building a suitable digital acquisition system

Meters which measure VDV directly, data recorders and post-processing software are now available

The details of the "recipe" have been retained and slightly fine-tuned in 3rd Edition

One area of fine tuning – theoretical vs. typical useable dynamic range of A - D converters

Theoretically 16 bit – 96 dB and 24 bit - 144 dB

In practice, good quality commercially available devices 16 Bit – 85 dB and 24 Bit 96 dB

Recording Instrumentation

Signal to Noise Ratio is another area where the 3rd Edition has Tempered Theory with Practicality

Difficult to find real world kit that will achieve a broadband 20 dB [20 log ($v_{rms\ signal}/v_{rms\ noise}$)] S/N Ratio for some sensitive equipment criteria or the low vibration levels normally associated with groundborne noise

3rd Edition suggests:-

- It's often more appropriate to consider spectral content of noise floor vs criteria
- May have to work at a S/N Ratio of 10 dB or less at some frequencies
- Measurements can still be acceptable as long as influence of noise floor is evaluated

3rd Edition also offers some specific guidance on noise floor for instrumentation used for Secondary measurement of groundborne noise

Recording Instrumentation

Frequency	Auditory Threshold	Estimated Vibration Equivalents of Auditory Thresholds		Suggested Maximum Third Octave Band Noise Floor	
(Hz)	dB SPL	Vel (mms^{-1})	Acc (ms^{-2})	Vel (mms^{-1})	Acc (ms^{-2})
25	68.7	0.11	0.017	0.011	0.0017
31.5	59.5	0.038	0.0074	0.0038	0.00074
40	51.1	0.014	0.0036	0.0014	0.00036
50	44.0	0.0063	0.002	0.00063	0.0002
63	37.5	0.003	0.0012	0.0003	0.00012
80	31.5	0.0015	0.00075	0.00015	0.000075
100	26.5	0.00084	0.00053	0.000084	0.000053
125	22.1	0.00051	0.0004	0.000051	0.00004
160	17.9	0.00031	0.00031	0.000031	0.000031
200	14.4	0.00021	0.00026	0.000021	0.000026
250	11.4	0.00015	0.00023	0.000015	0.000023

Table 10.3: Indicative Vibration Equivalents of Auditory Thresholds and Suggested Third Octave Noise Floor

Based on:-

Equation D 4 from Appendix D: *Lp = Lv – 32 dB*

Auditory Thresholds from BS EN ISO 226 (2003)

Proprietary Equipment: Table 10.4

Application	Instrumentation standard	Parameters required	Frequency range	Level range
BS 7385:2 and BS 5228:2 assessment	None but DIN 45669, ISEE or evidence of frequency response recommended	PPV, dominant frequency, displacement (below 4 Hz)	1 – 250 Hz	0.3 - > 50 mms^{-1}
BS 6472:1 assessment	ISO 8041-1	Weighted acceleration with W_b (vertical) and W_d (horizontal) frequency weighting and VDV	0.5 – 80 Hz	Indicative unweighted acceleration range 0.0005 – 10 ms^{-2}
BS 6472:2 assessment	None but DIN 45669, ISEE or evidence of frequency response recommended	PPV, unweighted sound pressure level	4.5 – 250 Hz (for vibration)	0.1 – 100 mms^{-1} (for vibration)
Groundborne noise	None	RMS third octave acceleration or velocity	16 – 250 Hz	* Indicative (unweighted) range 0.0005 – 10 ms^{-2} or 0.05 – 10 mms^{-1}
Specifying mitigation	None	RMS third octave acceleration or velocity	0.5 – 80 Hz (perceptible vibration) 16 – 250 Hz (groundborne noise)	* Indicative (unweighted) range 0.01 – 10 ms^{-2} or 0.01 – 10 mms^{-1}
Sensitive operations and machinery	None	RMS third octave velocity	1 – 80 Hz	* 0.003 (for the most stringent limit) – 5 mm s^{-1}

* It is more appropriate to consider the range and noise floor as a function of frequency e.g. octave/third octave bands for these applications

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Equipment Calibration

Calibration Regime for Sound Instrumentation Well-Established.

BS EN 61672: 1 performance standards for Class 1/Class 2 sound level meters.

BS EN 61672: 2 sets out the procedure for pattern evaluation (type testing) for sound level meters.

BS EN 61672: 3 sets out the procedure periodic testing of sound level meters.

BS EN 60942 sets out the performance standards and the procedures for pattern evaluation and periodic testing for acoustic calibrators.

Field Calibration.

Equipment Calibration

Calibration Regime for Vibration Instrumentation Less Well-Established.

Only 1/6 application areas (BS 6472: 1) has a clear instrumentation standard (BS EN ISO 8041)

No UK or international standard applicable to “PPV meters”

CERTIFICATE OF CALIBRATION

Date of Issue: 02 October 2019 **Certificate Number: TCRT19/1753**

Issued by:
ANV Measurement Systems
Beaufort Court
17 Roebuck Way
Milton Keynes MK5 8HL
Telephone 01908 642846 Fax 01908 642814
E-Mail: info@noise-and-vibration.co.uk
Web: www.noise-and-vibration.co.uk

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Approved Signatory

K. Mistry

Client	ANV Measurement Systems Beaufort Court, 17 Roebuck Way Milton Keynes MK5 8HL
Purchase Order No.	ANV MS Hire
Instrument	Rion VM-56 Tri-Axial Vibration Meter
Serial No.	00660056
Accelerometer Type	PV-83D
Accelerometer Serial No.	80062
Program	2.0
Client Asset No.	N/A
Procedure ID.	VM-56 Issue 1
Job Number	TRAC19/10437
Date of Calibration	02 Oct 2019
Previous Cert. number	N/A
Date of Previous Cert.	N/A
Rig Number	6
Kit Number	24
Calibration Status	Passed Calibration

This calibration is traceable to National Standards. ANV Measurement Systems sources used to perform calibrations are calibrated at the National Physical Laboratory or by UKAS laboratories accredited for the purpose.

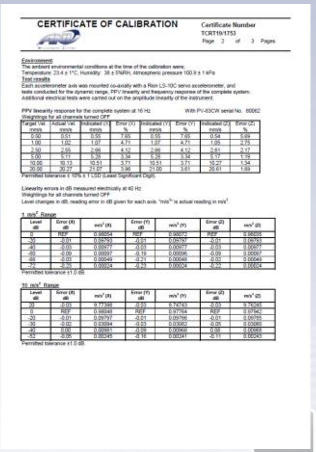
The performance of the system (the meter, accelerometer) was found to be within the manufacturer's specification.

Comment
This certificate reports recorded values for the instrument 'As Received'.

Equipment Calibration

Calibration Regime for Vibration Instrumentation Covered by BS EN ISO 8041

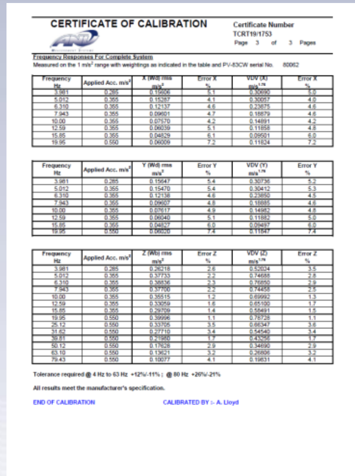
- Performance Specifications:- Manufacturer
- Pattern Evaluation:-
  - Frequency response, phase response, amplitude linearity, signal burst response
  - The influence of environmental and electromagnetic conditions
  - Detailed requirements on what needs to be in the manual
  - It is not established practice for manufacturers to get vibration meters “Type Tested”
- Validation:- for “one-off” instruments made by practitioners or researchers
  - A selection of tests from Pattern Evaluation


CERTIFICATE OF CALIBRATION
Certificate Number
TCRT19/1753
Page 2 of 3 Pages

Equipment Calibration

Calibration Regime for Vibration Instrumentation Covered by BS EN ISO 8041

- Periodic Testing:- Carried out by testing laboratory (calibration laboratory)
  - Maximum time between periodic verifications 24 months
  - Frequency response from 2 – 63 Hz measured at 1 ms^{-2}
  - Amplitude response from 0.1 - 10 ms^{-2} at 15.915 Hz
  - No testing of time response or whether the instrument computes VDV correctly
  - No UKAS accredited labs for vibration meters (some for accelerometers)



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Certificate Number
TCRT19/1753
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Frequency Responses For Complete System

Measured on the 1 m/s^2 range with weightings as indicated in the table and PV-83CW serial No. 80062

Frequency Hz	Applied Acc. m/s^2	X (Wd) rms m/s^2	Error X %	VDV (X) $m/s^{1.75}$	Error X %
3.981	0.285	0.15606	5.1	0.30690	5.0
5.012	0.355	0.15287	4.1	0.30057	4.0
6.310	0.355	0.12137	4.6	0.23875	4.6
7.943	0.355	0.09601	4.7	0.18879	4.6
10.00	0.355	0.07570	4.2	0.14891	4.2
12.59	0.355	0.06039	5.1	0.11858	4.8
15.85	0.355	0.04829	6.1	0.09501	6.0
19.95	0.550	0.06009	7.2	0.11824	7.2

Frequency Hz	Applied Acc. m/s^2	Y (Wd) rms m/s^2	Error Y %	VDV (Y) $m/s^{1.75}$	Error Y %
3.981	0.285	0.15647	5.4	0.30736	5.2
5.012	0.355	0.15470	5.4	0.30412	5.3
6.310	0.355	0.12138	4.6	0.23850	4.5
7.943	0.355	0.09607	4.8	0.18885	4.6
10.00	0.355	0.07617	4.9	0.14982	4.8
12.59	0.355	0.06040	5.1	0.11882	5.0
15.85	0.355	0.04827	6.0	0.09497	6.0
19.95	0.550	0.06020	7.4	0.11847	7.4

Frequency Hz	Applied Acc. m/s^2	Z (Wb) rms m/s^2	Error Z %	VDV (Z) $m/s^{1.75}$	Error Z %
3.981	0.285	0.26218	2.6	0.52024	3.5
5.012	0.355	0.37733	2.2	0.74688	2.8
6.310	0.355	0.38836	2.3	0.76850	2.9
7.943	0.355	0.37700	2.2	0.74458	2.5
10.00	0.355	0.35515	1.2	0.69992	1.3
12.59	0.355	0.33059	1.6	0.65100	1.7
15.85	0.355	0.29709	1.4	0.58491	1.5
19.95	0.550	0.39996	1.1	0.78728	1.1
25.12	0.550	0.33705	3.5	0.66347	3.6
31.62	0.550	0.27710	3.4	0.54540	3.4
39.81	0.550	0.21980	1.7	0.43256	1.7
50.12	0.550	0.17628	2.9	0.34690	2.9
63.10	0.550	0.13621	3.2	0.26806	3.2
79.43	0.550	0.10077	4.1	0.19831	4.1

Tolerance required @ 4 Hz to 63 Hz +12%/-11% ; @ 80 Hz +26%/-21%

All results meet the manufacturer's specification.

END OF CALIBRATION   CALIBRATED BY :- A. Lloyd

Equipment Calibration

Calibration Regime for Vibration Instrumentation Covered by BS EN ISO 8041

In-situ Checks:- carried out by practitioners in the field before and after measurements

Set out in terms of what should be in the instrument documentation including:-

Instructions of a preliminary check of the instrumentation and connections

A procedure for checking the vibration sensitivity a 15.915 Hz using a specified field calibrator

Some people have inferred from this that application of a field calibrator is mandatory but This is not so because a note which states:-

"If, according to gained experience, it can be assumed that the sensitivity of transducer and instrument do not alter, a quantitative determination of the overall sensitivity of the vibration meter can be omitted. In this case, however, a mechanical overall tapping test is mandatory to demonstrate that the signal path is uninterrupted."

Equipment Calibration

Calibration Regime for Velocity-Based Vibration Instrumentation

Performance Specifications:- No UK Standard – Manufacturer may claim DIN 45669 &/or I.S.E.E.

Pattern Evaluation:- There is a procedure set out in DIN 45669 but suited specifically to DIN 4150 use

Periodic Testing:- Some tests from DIN 45669 “Verification Testing” potentially applicable

In-situ Checks:- As noted by DIN 45669 “Quantitative testing of vibration measuring systems at the place of use (on site, in situ) is frequently only possible to a limited extent or is not possible at all.”

The transducers for velocity-based systems are typically 3-D geophones weighing ~ 4.5 kg

There are some calibrators available that can deal with a mass of 4.5 kg or more

Such calibrators only operate in the vertical plane – no use with horizontal geophones

DIN 45669 requires a tap test to ensure basic functionality and connection of system

Equipment Calibration

Benefits of Quantitative Vibration Field Calibration

Although neither mandatory nor universal professional practice, the authors' panel recognised field Calibration does offer benefits.

- Especially for modular systems with gain/sensitivity settings at several points in the signal chain
- For sensitivity checking when wav files are going to be shared with a third party
- Enhanced confidence in survey results

The authors' panel also recognised that field Calibration:

- Is considered best practice by some practitioners; and
- May be a requirement for some projects

Equipment Calibration

Periodic (Laboratory) Verification - All Groundborne Vibration Instruments

- Calibration Regime for Vibration Instrumentation Less Well-Established than that for sound.
- Not established practice for manufacturers to submit instruments for Pattern Evaluation (Type Testing)
- Periodic Tests set out for acceleration-based instruments in BS EN ISO 8041.
  - Not in the same level of detail as set out in the standards for acoustic instruments
  - No requirement to check whether the instrument is calculating VDV correctly
- Periodic Tests for vibration based instruments can be found in DIN 45669
  - Don't directly address the way instruments are used in the UK
- The procedures carried out by laboratories offering periodic tests could vary considerably
  - Recommendation: - obtain a sample certificate from the lab prior to submitting an instrument to Establish whether the tests cover ranges and parameters (e.g. VDV) that you require.

THANK YOU!