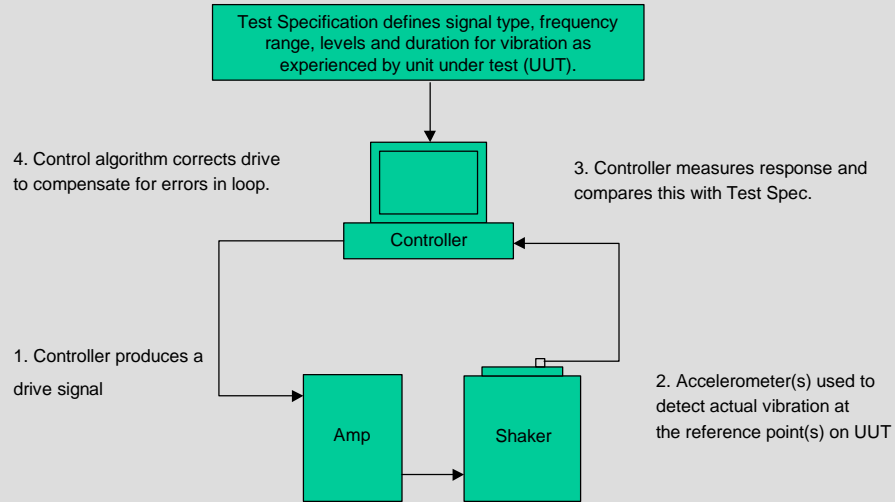

Analysing the Vibration Controller Closed Loop chain

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This paper investigates the sources of uncertainty in a vibration test system that uses a modern vibration controller system.

The closed loop is reviewed and an example uncertainty budget model is developed.

The essence of vibration control



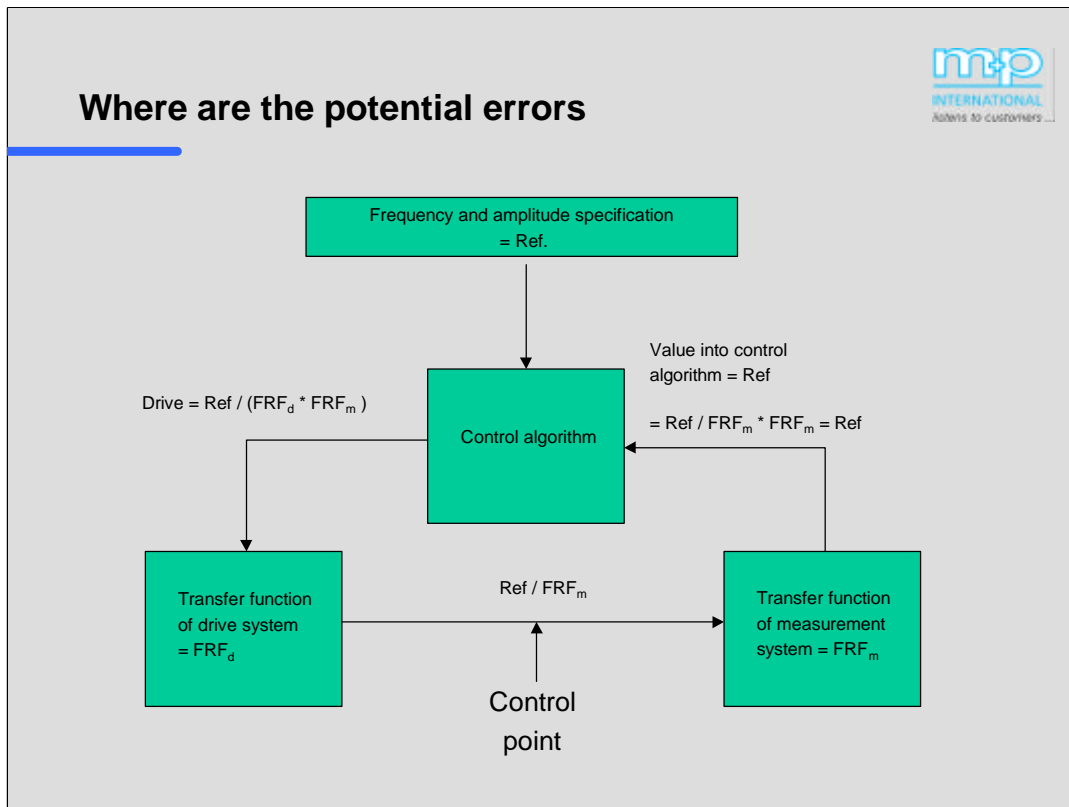
The slide shows the basic vibration control loop.

The test specification is entered into the controller to define the required frequency content and amplitude at the shaker table.

The controller generates a drive signal to the amplifier and shaker. The resultant vibration is measured by an accelerometer near the unit under test (UUT) and fed via charge amplifier back to the vibration controller. The control algorithm within the controller compensates for errors in the feedback signal such that the new drive will produce the correct frequency content and amplitude at the monitor point.

Since we can assume that with today's powerful PC's and well developed algorithms that the controller can perfectly correct the loop where do the test uncertainties appear.

Where are the potential errors



The control loop is shown here in terms of the processing elements. The test specification defines the reference spectrum and levels (Ref). It is assumed that the control algorithm is accurate.

The control algorithm computes a drive function so that its Ref input is equal to the input from the measurement control point.

As is seen the resulting control point is dependant on the transfer function (or errors) within the measurement chain whereas the transfer function of the drive chain is fully corrected.

Hence if we characterise the measurement chain we can define the control uncertainty.

What data is required

- **Objective is to quantify how accurate our simulation is compared to the test specification.**
- **Typical test specifications contain a range of both test frequencies and levels.**
 - Do we want one overall uncertainty covering the entire test scope
 - Do we want values at a number of discrete frequencies
- **What factors introduce amplitude uncertainties**
 - basic calibration
 - amplitude variations with frequency
 - linearity, ie amplitude changes dependant on amplitude
 - changes with temperature
 - variation with time
 - resolution available
 - noise sources

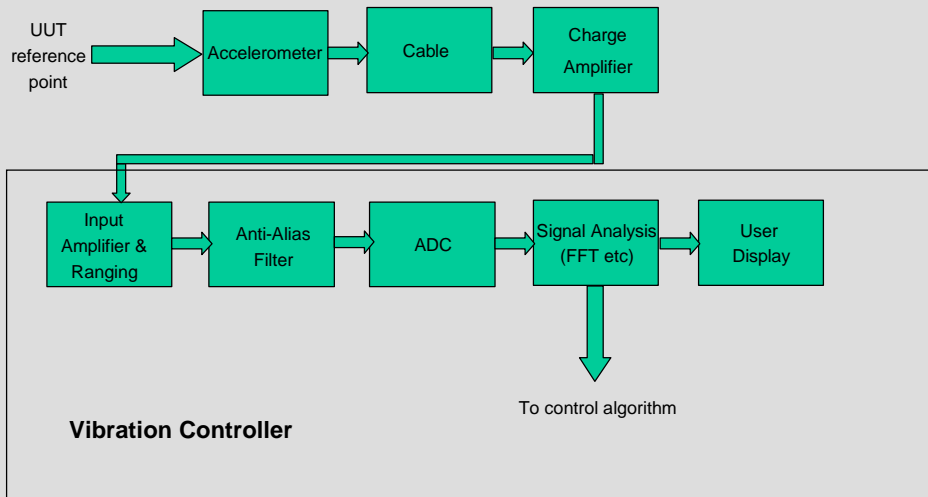
There are a number of ways that the test uncertainties could be defined. A global value that applies over all frequencies and amplitudes could be developed. This would likely be a higher value than looking at a single frequency but would be simpler to use and understand.

A more refined approach may be to develop a set of values over a range of frequencies and amplitudes that could be applied to specific test requirements. Also a way of reducing uncertainty would be to develop a calibration data set to eliminate systematic errors depending on test frequency and level.

In either case the slide shows some typical factors that have to be considered for each component of the measurement chain.

Sources of uncertainty

1. The measurement chain

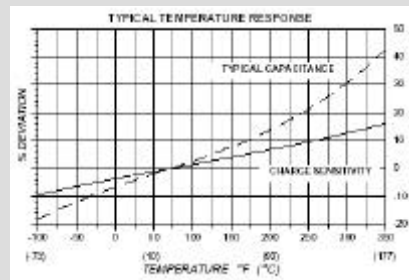
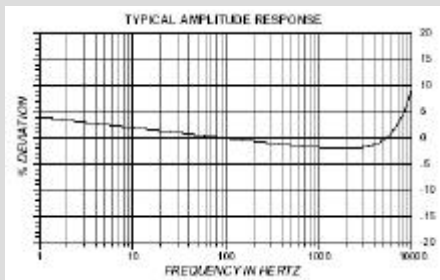


The measurement chain breaks down into a number of elements for which we can normally get accuracy or uncertainty data.

The sensor

DYNAMIC CHARACTERISTICS Units

CHARGE SENSITIVITY	TYPICAL pC/g 12.0
AMPLITUDE RESPONSE	±5% Hz 1 to 6000 ±1dB Hz .5 to 6000
TEMPERATURE RESPONSE	See Typical Curve
TRANSVERSE SENSITIVITY	±3%
AMPLITUDE LINEARITY	<1% Per 250 g, 0 to 1000 g



- but what about calibration uncertainty?
- 3% at 95% confidence typical

It is still common practice to use charge accelerometers in environmental vibration test.

Here are some typical data drawn from a general purpose device.

Normally we must consider each component of error as “additive”.

Every accelerometer has a sensitivity value, eg 12.6 pC/g. This is often considered as a global sensitivity but closer inspection of the data above indicates that there are many other factors. The sensitivity applies at one frequency eg 100 Hz in example but this is modified by systematic variations over both frequency and temperature. Also more subtle effects occur due to transverse sensitivity, base strain and linearity. These should all be considered and included within the budget calculation where significant.

Also do not forget the basic calibration uncertainty associated with the normalised sensitivity.

The cable

- Common practice is to use charge accelerometers
- Charge cables can be a significant source of noise

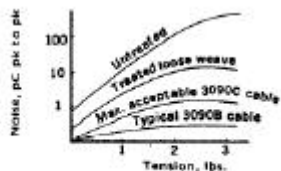


Figure 2. Noise vs tension for 9 ft section of unsupported cable vibrated at 20 g, 40 Hz

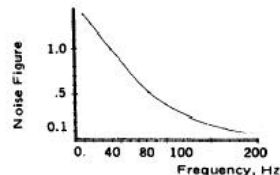


Figure 1. Noise figure vs frequency for 3090C cable

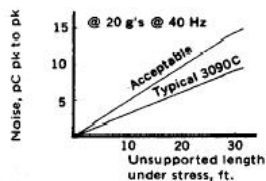


Figure 3. Noise vs unsupported length for 3090C cable vibrated at 20 g, 40 Hz

- Example: 20g at 20Hz produces 1 pC rms on a good cable.
- So with an ill-chosen 1 pC/g accelerometer this would add 5% to the response.

Cable noise becomes significant at low frequency.

The extracts show some data from Endevco that could result in an additional 5% error in a badly chosen test set up.

Even a good set-up should consider a 0.5% uncertainty at 20Hz.

The charge amplifier

TRANSFER CHARACTERISTICS

GAIN ACCURACY $\pm 1\%$ ($\pm 2\%$ with source impedance less than 10 kohm or greater than 10 kpF)

Gain Stability vs. Temperature $\pm 0.02\%/^{\circ}\text{F}$ maximum

FREQUENCY RESPONSE Flat within its bandwidth.

The gain at the upper and lower cut-off frequency is 5% lower than the gain at 1 kHz.

Lower Cut-off Frequency

The lower cut-off frequency is dependent on the input shunt resistance as follows:

1 Hz N.A.

3 Hz >100 kohm

5 Hz 10 kohm to 100 kohm

50 Hz 1kohm to 10 kohm

Upper Cut-off Frequency 10 kHz

Charge amplifiers have typical analogue specifications associated with gain setting accuracy, frequency response and temperature stability. These can all be added to the margin calculation.

Again these factors are usually “additive”.

Frequency response could be applied as a calibration to eliminate this error.

The vibration controller front-end

- **Unhelpful data**
 - dynamic range
 - number of ADC bits
 - etc

- **A better analogue specification**
 - Amplitude accuracy at 1kHz +/- 0.5%
 - Linearity +/- 0.01% of range
 - Flatness +/- 1%

- **Even better - UKAS style**
 - array of “system” calibration points across a range of frequencies and amplitudes
 - eg spec: <1% from 20mV to 2V rms and 5Hz to 2000Hz over 12 months, 23degC +/- 5degC.

Dynamic range, ADC bit length etc do not provide useful data for uncertainty calculations. Although it would be wrong to say that these parameters do not contribute their effect is insignificant, eg 1 bit in 16 represents 0.003%

We should look for absolute accuracy data. As with the charge amp typical analogue specs should provide data for accuracy (at a spot frequency), flatness over the frequency range and linearity.

An even better approach follows from the UKAS preferred calibration methods that test the controller system over a range of amplitudes at a number of frequencies over the operating window.

A global uncertainty can hence easily be identified.

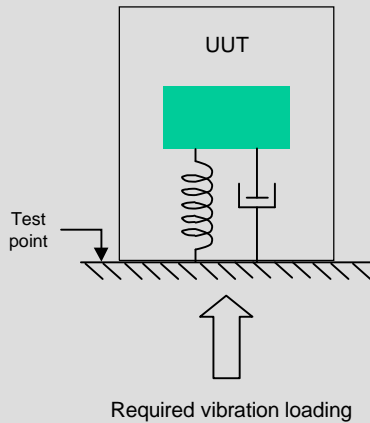
Reading results data

- **Display resolution can add additional uncertainty**
- **Typical 4 digit amplitude readout**
 - 1 in 9999 is only 0.01%
 - 1 in 1000 is additional 0.1%

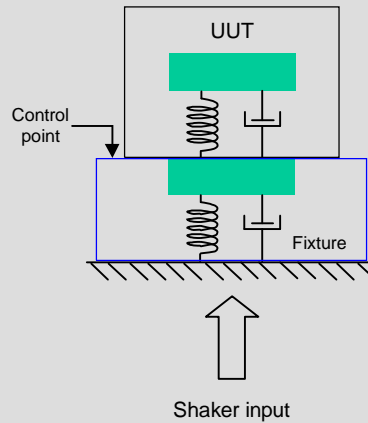
Although unlikely to be significant, consideration of data presentation should be given. This example indicates a possible uncertainty from a 4 digit readout as it reaches the lower end of its range.

Other sources of errors

Ideal test scenario:



Normal test scenario:



Fixture performance can greatly effect the vibration loading experience by the UUT.
Position of control channel(s) can also cause large changes.

A critical assumption made is that the UUT experiences the vibration as measured by the control accelerometer. Although beyond the scope of most uncertainty budget calculations everyone who designs fixtures or has placed control accelerometers will be aware of just how critical this assumption is.

With a well developed uncertainty budget we can at least say what the vibration is at the point of measurement.

Other sources of error

- **Drive non-linearity**
 - amplifier overload
 - shaker linearity (esp. low frequency)
 - fixture
- **Controller will typically filter out noise**
- **Result is that UUT will experience higher levels than are being displayed.**

The initial loop analysis assumed a linear control loop - another big leap in many applications.

Typically the drive chain will create non-linear responses that the controller may ignore depending on the test type and filtering settings.

The end result is that the UUT will generally experience a rather greater level than is measured by the control loop. A small over-test is probably better than under-test in most applications.

Some controllers will allow a number of measurement filters to be applied other than those being used by the closed loop. This may allow signal quality factors to be assessed where necessary.

Conclusions

- **Linear closed loop uncertainty is determined by the measurement chain**
- **This can be broken down and each component analysed**
- **The uncertainty budget calculation can be used to combine the elements and provide a global test value.**

References

1. Applying accelerometer cable noise specifications to test situations.
Endevco Technical Data ref. A534.
2. Measurement uncertainty budget calculator
Download from <http://www.mpiuk.co.uk/download/uncertainty.xls>