Primary vibration calibration by laser interferometry – requirements, problems and first experience with a new calibration system

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ABSTRACT

Primary vibration calibration according to ISO 16063 can be carried out in several ways using different methods. Because of the wide frequency range and the possibility to calibrate sensitivity magnitude and phase, method 3 of part 21 of the international standard is mostly used in practice. Several requirements for components, system integration and control of the system must be met to achieve the goals of the standard and obtain low uncertainties in measurement and calibration. Illustrated by the CS18P primary calibration system of SPEKTRA, the main requirements, special problems and well-investigated solutions will be discussed. It will be shown that the all-digital vibrometer of Polytec plays an important part but, in addition to that, system integration and optimization of all components must be implemented with great care by calibration specialists. Our paper comes to the conclusion that, for primary calibration, high quality components alone will not be enough. It is necessary to integrate these components in an optimized system that takes into consideration all requirements and influences and so allows to reduce the uncertainties of the calibration procedure to the lowest possible values.

Keywords: vibration, calibration, primary, secondary, acceleration, interferometer, vibrometer, sensitivity, phase, uncertainty

1. INTRODUCTION

In recent years the older standards concerning the calibration of vibration and shock transducers have completely been revised. Result of these activities is a new series “Methods for the calibration of vibration and shock transducers, ISO16063-xx“. This revision was sparked off by new requirements in international and worldwide co-operation and the possibility to use new technologies or well-known technologies at a higher level.

The calibration method most frequently used in practice for the calibration of vibration sensors is secondary calibration according to ISO 16063 Part 21 [1].

Fig. 1: Main component parts of a secondary calibration system CS18 MF

As shown in Fig. 1, the main components of such a system are:

- Vibration generator
- Vibration exciter with power amplifier
- Back-to-back reference standard
- Signal conditioning and data acquisition unit for reference standard and device under test
- Vibration Control Unit for measurement, control and user software interface

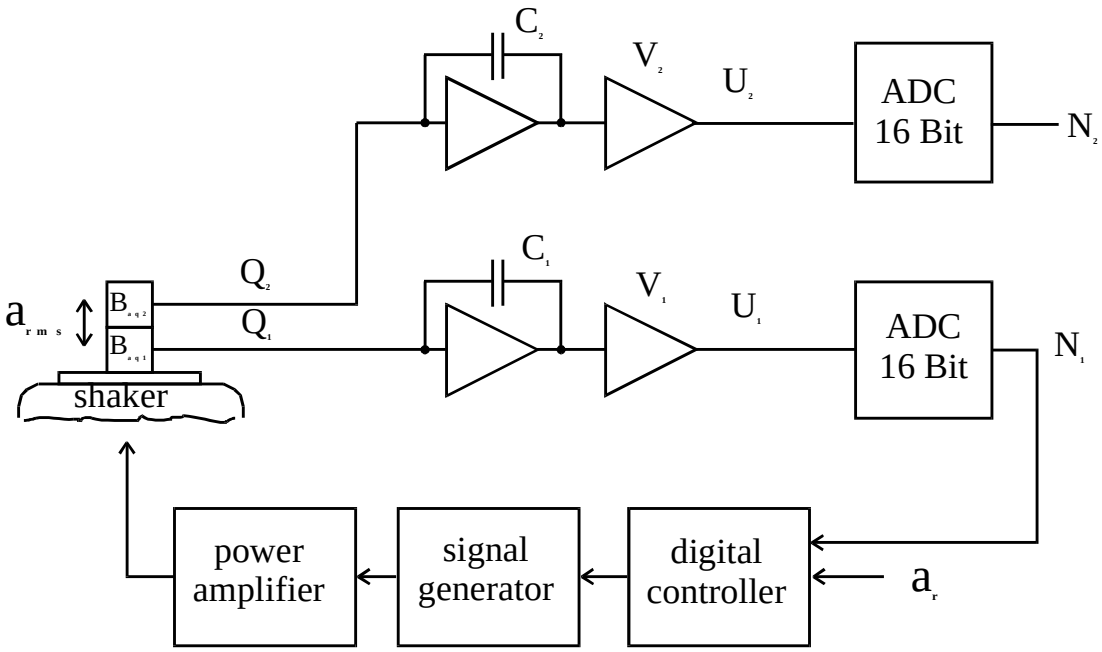

Fig. 2: Block diagram of secondary calibration system CS18 MF

In this case the device under test is compared with a reference standard accelerometer (see Fig. 2). This reference standard must have been calibrated before at a higher level, e.g. by PTB in Germany using primary calibration.

Part 11 of the new ISO standard describes methods of primary calibration by laser interferometry. In this case the unknown excitation value – acceleration, vibration velocity or vibration displacement – is traced back directly to the wavelength of the laser light [2].

2. NEW ISO STANDARD 16063

The new ISO standard deals with “Methods for the calibration of vibration and shock transducers” (see Fig. 3).

ISO 16063-1	Basic concepts
ISO 16063-11	**Primary vibration calibration by laser interferometry**
ISO 16063-12	Primary vibration calibration by the reciprocity method
ISO 16063-13	Primary shock calibration using laser interferometry
ISO 16063-21	**Secondary vibration calibration**
ISO 16063-22	Secondary shock calibration

Fig. 3: Parts of ISO 16063 (abstract)

The standard includes Parts for the sine calibration of vibration sensors and methods for the calibration of shock transducers by shock excitation. This paper is focussed on the methods for the sine calibration of vibration sensors at primary level as described in ISO 16063 Part 11: “Primary vibration calibration by laser interferometry”.

In standard ISO 16063-11, various methods of primary calibration are described.

Method 1: “Fringe-counting method”

This method is applicable to sensitivity magnitude calibration in the frequency range from 1 Hz up to 800 Hz.

Method 2: “Minimum-point method”

This method is applicable to sensitivity magnitude calibration in the frequency range from 800 Hz up to 10,000 Hz.

Method 3: “Sine-approximation method”

This method is applicable to sensitivity magnitude and phase calibration in the frequency range from 1 Hz up to 10,000 Hz.

Because of its benefits of wide frequency and amplitude ranges and its ability to measure both amplitude and phase of the vibration signal, SPEKTRA has integrated a Primary Option based on Method 3 “Sine-Approximation Method“ in their Calibration System CS18.

3. PRACTICAL ASPECTS

3.1 General requirements

Due to the high precision of laser interferometers, primary calibration with very low uncertainty is obviously not too difficult to achieve. As the prices of these components are getting more and more acceptable, such systems will in future be installed not only in national metrology laboratories but also in highly specialized accredited industrial calibration laboratories.

Fig. 4: Main component parts of a primary calibration system CS18P HF

As shown in Fig. 4 and 5, the main components of such a system are:

- Vibration generator
- Vibration exciter with power amplifier
- Laser interferometer with vibration-isolating foundation
  (as opposed to the back-to-back reference standard transducer used in secondary calibration)
- Signal conditioning and data acquisition unit for the device under test
- Vibration Control Unit for measurement, control and user software interface

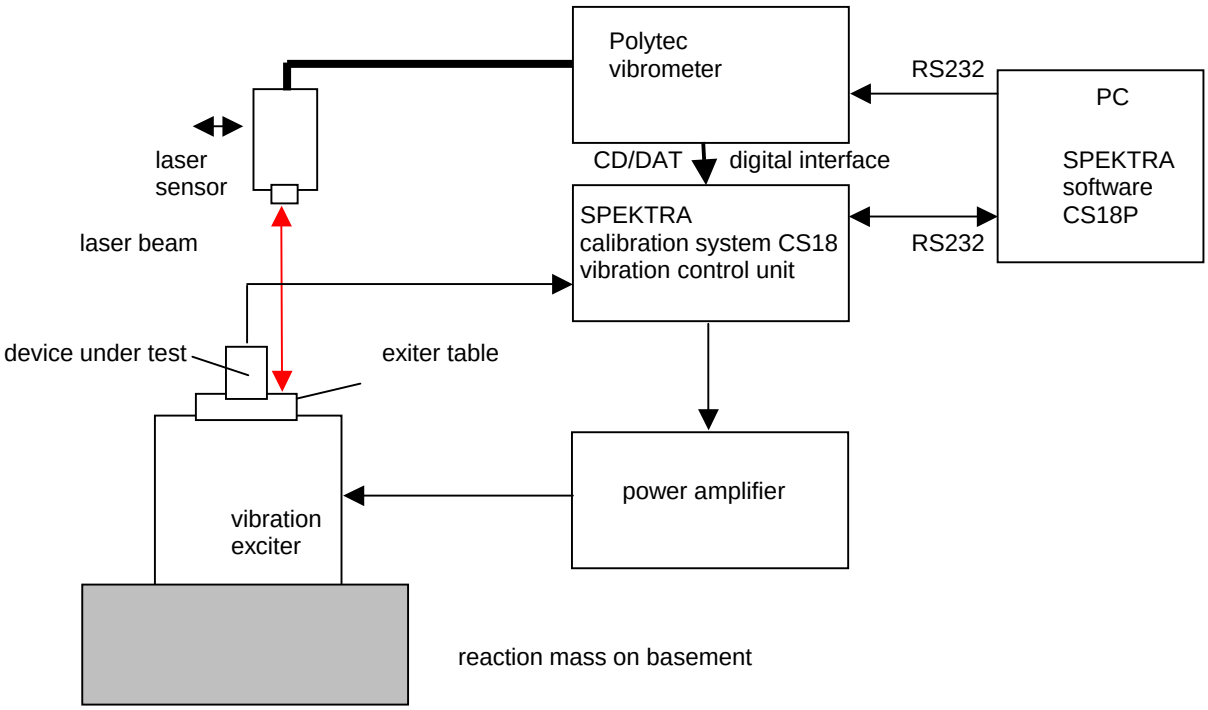

Fig. 5: Block diagram of primary calibration system CS18P HF

In order to fulfil all requirements of ISO standard 16063-11 it is necessary to make use of high quality components. The vibrometer is without question the main component part needed for carrying out primary calibration. SPEKTRA successfully integrated a Polytec type with all-digital interface in the control and measurement unit. The vibration exciter generates the mechanical excitation signal to which the device under test (DUT) is exposed. The instrumentation has to be so designed that there are only very small transverse and rocking motions over a wide frequency and amplitude range. In practice this is definitely a major problem, because it is not possible to completely suppress any motion in some other axis when generating the mechanical excitation signal in the desired direction.

At first glance it seems sufficient to combine a very good vibration exciter with an excellent vibrometer and voltmeter to be successful in primary calibration. Unfortunately, this is not sufficient.

3.2 Requirements for components

In order to obtain very low uncertainties in calibration, a number of requirements for components, test procedure and global configuration must be met.

Frequency stability and uncertainty: ± 0.05 %

The absolute value of the excitation frequency and its stability can be ensured without practical problems by an all-digital generator/controller traced back to a stable enough quartz oscillator.

Acceleration stability and uncertainty: ± 0.05 %

Obtaining the required high stability of acceleration is not a trivial problem. Because of long and short-term instabilities of the driving coil of the shaker (caused by heating effects), acceleration may vary. To avoid this variation, a controller has to be included as shown in Fig. 6.

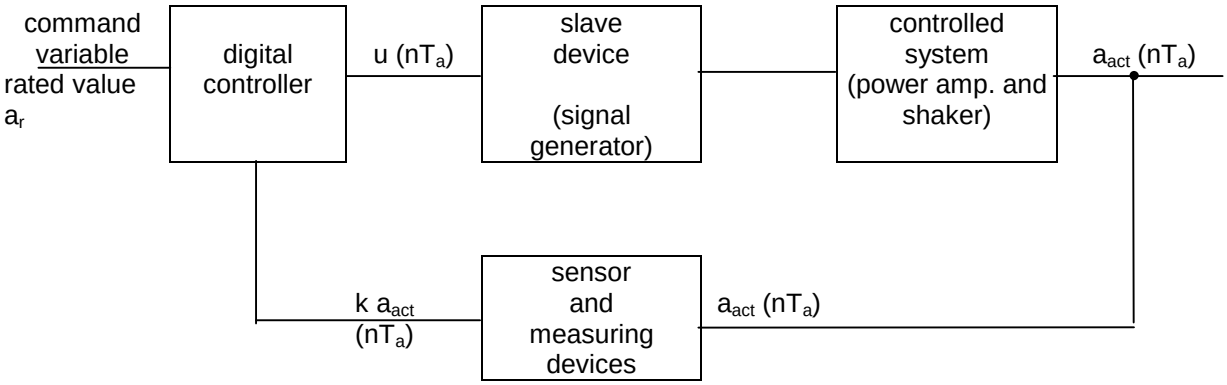

Fig. 6: Control loop to maintain constant acceleration
a_{act} = actual acceleration, a_r = rated value of acceleration, T_a = sampling period

Using a so called PID controller, the control algorithm is given by

$$\Delta U(n) = \Delta U(n-1) + P \bullet E(n) - (P+I) \bullet E(n-1)$$

$$E(n) = k\,(a_r - a_{act})$$

Although these equations look very simple it is not easy to control actual acceleration a_{act} with very short delay time. If sine approximation is used one has to wait for a number of periods of the signal frequency to obtain proper results. As a consequence the controller has a considerable dead time which makes it rather slow.

Using the well known principle of calculating the r.m.s. value by squaring and low pass filtering, the settling time depends on the characteristics of the low pass. In this case short settling time will result in large ripple and low ripple in long settling time. To overcome said contradiction, a special combination of a low pass filter and a band stop filter is used in SPEKTRA systems (see Fig. 7) which has a 1% settling time of less than one period of the signal frequency. This method is only used, however, to feed the controller, whereas for measuring actual acceleration (following method 3 of the standard), sine approximation is applied.

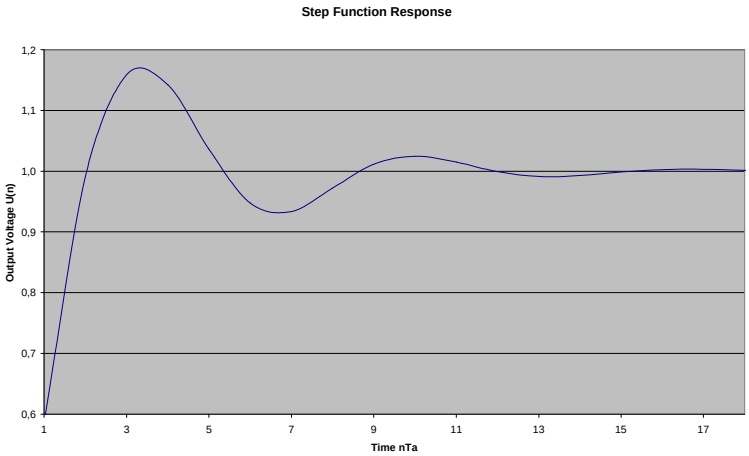

Fig. 7: Step function response of a low pass / band stop filter combination (f_{notch} = 2 f_{signal})

Irrespective of the used control algorithm, some small control deviation and small ripple of the controlled acceleration signal will still remain. Further improvement can be obtained by opening the control loop for the duration needed to get the samples for sine approximation after the controller has settled to a predefined deviation.

Total harmonic distortion (THD): < 2%

Especially at lower frequencies it is not easy to provide for low distortion. Sometimes THD can successfully be minimized by using special control algorithms [3]. For primary calibration, air-bearinged shakers with low THD are used.

Transverse, bending and rocking movements: < 10 Hz: < 1%, > 10 Hz: < 10%

This is in practice a real problem. Because of the wide ranges of frequency, excitation amplitude, moving mass etc., no exciter can constantly ensure low cross or rocking movement. Some resonances will inevitably occur in this wide range. Special calibration exciters are so designed that these effects are minimum, but this can in practice only be ensured in a limited range. So these effects have to be taken into account when calculating measurement uncertainty and the measurement procedure must be so optimized that these influences are minimum.

As regards the DUT and its transverse sensitivity, this effect has to be included into the uncertainty budget. The transverse sensitivity of a high quality sensor is normally lower than 3%. That means that a cross motion with an amplitude of 10% of the main excitation signal may result in a 0.3% too high or too low output signal of the sensor.

Concerning the non-contacting measurement of the vibration displacement of the exciter table, there is a way to minimize these effects by measuring at several points around the DUT or on its surface (if it is a back-to-back one) and calculating the mean value.

Voltage generation / measurement: < 0.1%

This will be discussed later in section 3.3, because this is of special importance in a primary calibration system.

Environmental conditions: Noise, Humidity ...

Primary calibration requires special laboratory conditions like air conditioning, installation on a vibration-isolated foundation. To minimize vibration influences from other parts of the building it is helpful to install the system on a heavy and compact block of concrete in the basement of a building.

Vibration isolation: Vibrometer / Exciter

To exclude any influence from the relative movement between shaker and vibrometer, an optimized vibration-isolating foundation in adjustable configuration must be used. If different shakers shall be used in the system, the vibration-isolating foundation should be so designed that it can be adapted to different directions as shown, for example, in Fig. 8 and 9.

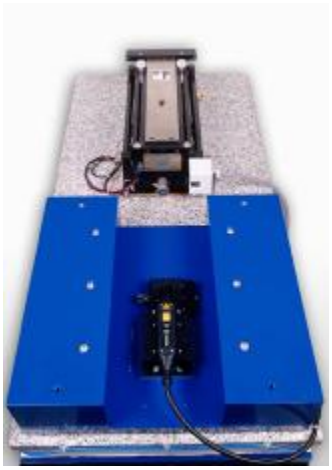

Fig. 8: CS18P STF, horizontal excitation

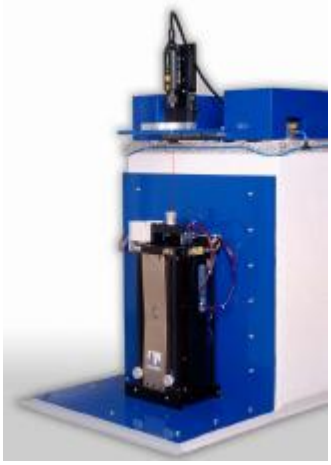

Fig. 9: CS18P STF, vertical excitation

3.3 Integration of controller, vibrometer and AC measurement

Laser Interferometer

The requirements for the vibrometer will be discussed in the paper by Polytec [6]. It has been important for the implementation of the primary vibration calibration system that in the new generation an all-digital standard SP/DIF-interface is used to get the velocity data continuously. This means that every special optical, mechanical, electrical and digital component can be optimized by the manufacturer according to the ISO standard.

Primary calibration means in our case that the vibration quantity (vibration displacement, velocity or acceleration) is directly traced back to the wavelength of the laser light inside the vibrometer. With the

new generation, there is no need for additional D/A-conversion in the vibrometer and A/D-conversion in the measuring unit.

The sensitivity of an accelerometer is defined by the ratio of the electrical output signal (charge or voltage) and the applied acceleration. Thus it makes little sense to measure the acceleration by an all-digital primary vibrometer with very high precision if, on the other hand, no efforts are made to measure the analogue electrical quantity with similar precision.

In fact, the most difficult problem in practice is the measurement of the transducers output signal and the phase shift between this signal and the acceleration signal according to method 3 of the standard.

Voltage generation / measurement: < 0.1%

It is a very hard requirement to demand that for all ranges and combinations of

- Frequency
- Gain
- Excitation

and for all types of electrical inputs such as

- Charge sensors
- Voltage sensors (e.g. sensor with external signal conditioner)
- Current-driven voltage sensors (e.g. ICP®)

an absolute uncertainty of less than 0.1 % of the AC-measurement be ensured. There are two ways to meet this goal:

1. Electrical calibration of the relevant signal path at selected frequencies under identical electrical conditions each time before a vibration calibration run is started. Because calibration has to include the complete measurement chain including the method 3 sine approximation algorithm, it is not easy to provide for the conditions to do so. Moreover several high quality and separately calibrated instruments such as reference condenser (Ref-C), digital voltmeter (DVM), high precision electrical attenuator and so on must be available for each calibration run.
2. Electrical calibration of the whole system in all combinations once at the time when the system is supplied and recalibration in acceptable intervals, typically once a year. In this case the electronic unit not only has to guarantee very good short-term stability but excellent long-term stability as well.

Because it is difficult for common end users to ensure optimum electrical conditions for the electrical calibration, SPEKTRA prefers the second procedure. The first procedure includes the risk that the condition under which calibration is carried out differ from time to time and from the reference conditions with well known and minimized disturbances.

The following problems concerning the electrical calibration of the vibration control unit can be minimized by keeping to special reference conditions in the SPEKTRA laboratory:

- 50 Hz or 100 Hz disturbances
- Shield, analogue and digital ground of any part of the system can be connected in a repeatable manner.
- The mutual influences of any additional equipment such as Generator, Digital Voltmeter, Attenuator, Reference-Condenser ... can be investigated and eliminated or minimized.
- A big problem is to calibrate the sine approximation measuring system (narrow band) by means of the only available high resolution and precision wide band DVM, e.g. the Hewlett Packard type (see Fig. 10).
- By using an all-automatic electrical calibration system, the measurements can be checked for stability and averaged for highest resolution.
- In order to use the system for phase calibration, it is necessary to measure the phase shift of all inputs and amplifications in relation to the digital input of the vibrometer. The used equipment has to be calibrated for this purpose using special procedures.

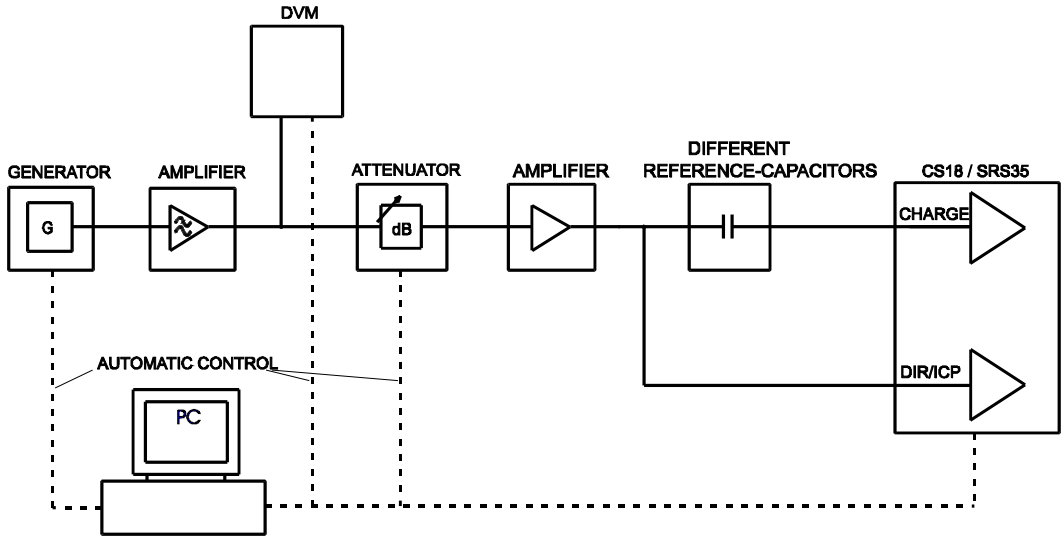

Fig. 10: System configuration for the electrical calibration of Vibration Control Unit of CS18

The electrical calibration of charge and voltage inputs with respect to amplitude and phase over the full frequency range and gain ranges –12dB ... 66dB with an uncertainty of less than 0.2 % was one of the most sophisticated operations of the project. The goal could be met for the special-purpose calibration hardware of the SPEKTRA CS18 system.

What we had to learn was to accept that every combination of separate electronic devices requires a special concept to obtain the lowest possible uncertainties in measurement.

Combination of Vibrometer, Controller and measuring unit

In order to be able to measure both the amplitude and the phase shift between the signal of the device under test and the acceleration signal of the exciter as a function of frequency, it is necessary to have a defined link between all components involved as shown in Fig. 11.

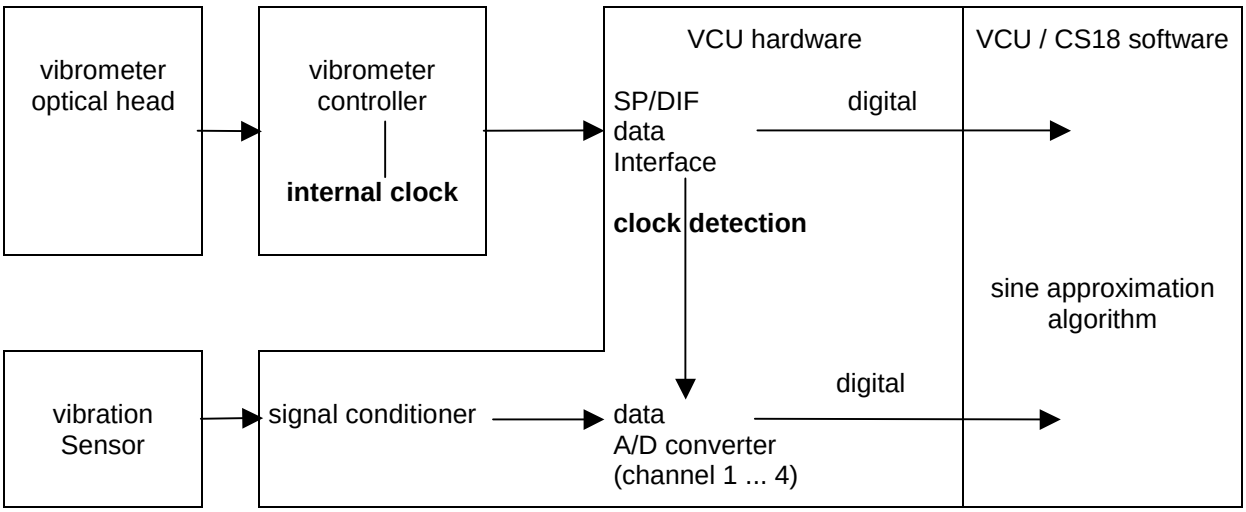

Fig. 11: Block diagram of system clock management

In particular it is necessary to synchronize the vibrometer with the vibration control unit (VCU). As regards the CS18 system, this is done by using the clock pulse used for serial transmission from the vibrometer to the VCU to generate the sample clock pulse for the A/D-conversion in the analogue parts. Because this clock pulse originates from the vibrometer where it is internally used for all sampling activities and calculations, there is a close connection between the mechanical and the electrical measurements in the primary vibration calibration system CS18P. In this manner it is possible to measure sensitivity magnitude and phase shift versus frequency with uncertainties according to the ISO standard.

3.4 Laser beam adjustment

Because of the cross and rocking motion of the vibration exciter head, it is not sufficient to take measurements only at one point (see Fig. 12).

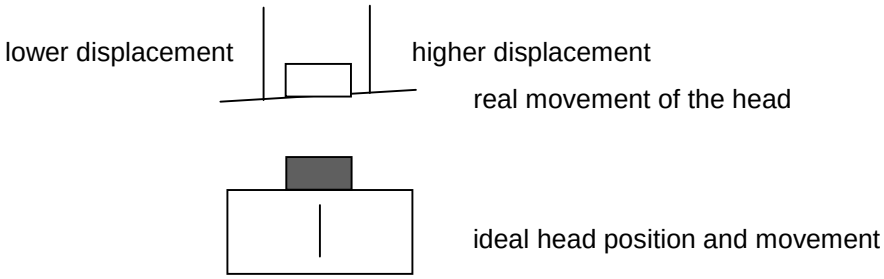

Fig. 12: Beam adjustment

If it were possible to take measurements in the middle of the head at only one point, this would be sufficient because the vibration at this point is the average of the motion of the sensor mounting surface. In practice, however, it is necessary to measure the excitation at several points close to the sensor edge on the exciter head. To get valid data the following conditions must be kept:

- The vibration signal must be absolutely repeatable
- The vibration must be stable for a longer period of time
- The air pressure of the air bearing of the shaker must be very stable, since the cross movement may be altered by differences in pressure

Only if all conditions are fulfilled, it is possible to measure step by step at several points and calculate the average of acceleration or complex sensitivity.

3.5 Sine approximation

The analog to digital converter yields a set of samples

$$\{U(1),\ U(2), U(3) \ldots U(N)\}$$

Assuming that the function

$$y(n) = a + b\,\sin[x(n) + c] \quad where \;\; x(n) = 2p\;\frac{f}{f_a} n$$

is hidden in the set of samples, the best approximation is obtained by demanding that the sum of the squared differences tends to be zero

$$SU = \sum_1^N [y(n) - U(n)]^2 \Rightarrow 0 \quad .$$

By using the partial derivatives

$$\frac{\partial SU}{\partial a}, \quad \frac{\partial SU}{\partial b} \quad and \quad \frac{\partial SU}{\partial c}$$

one gets a set of 3 equations from which the unknown quantities a, b and c can be obtained:

$$a = \frac{1}{N}\sum_1^N U(n) \;, \qquad b = \frac{2}{N}\sum_1^N U(n)\sin[x(n) + c] \;, \qquad \tan c = \frac{\sum_1^N U(n)\cos[x(n)]}{\sum_1^N U(n)\sin[x(n)]}$$

For the practical application of this approximation method it is important to learn how the algorithm responds to distortions like low frequency drift, hum, harmonics of the signal itself or other parasitic signals.

Detailed investigations revealed that the rejection of interference voltage is much worse than the rejection effect of a narrow band filter formerly used for secondary calibration (without optional extra *PHASE*).

If such distortions cannot be avoided by practical means (shielding, proper grounding), there is only one way for improving rejection: to increase the number of samples.

An improved measuring procedure using digital narrow band filters in both channels had been developed by SPEKTRA but this procedure is not in line with method 3 of the standard.

4. CONCLUSION

This paper specifies the requirements of the ISO standard and discusses practical problems not only from the point of view of one component or one special detail of the system. The paper is focussed on the main topic of a calibration system – measurement uncertainty – and all factors taking an influence on it. It will be shown that it is most beneficial to obtain the values from the vibrometer in an all-digital way, but this requires special synchronization of vibrometer and measuring unit. In order to successfully calibrate a sensor, measuring the excitation signal in a non-reactive way is only half the job. The charge or voltage output signal of the device under test must also be measured with the highest possible “absolute” precision in a wide range of sensitivity and frequency.

Our paper comes to the conclusion that for primary calibration, high quality components alone will not be enough. It is necessary to integrate these components in an optimized system that takes into consideration all requirements and influences and so allows to reduce the uncertainties of the calibration procedure to the lowest possible values. The influence of components as well as relevant questions of mechanical adaptation, vibration isolation, AD conversion and digital signal processing are discussed.

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