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DEPARTMENT OF CONTROL AND INSTRUMENTATION

ÚSTAV AUTOMATIZACE A MĚŘICÍ TECHNIKY

COMPACT MEASUREMENT SYSTEM FOR CALIBRATION OF VIBRATION SENSORS

KOMPAKTNÍ MĚŘICÍ SYSTÉM PRO KALIBRACI SNÍMAČŮ VIBRACÍ

BACHELOR'S THESIS
BAKALÁŘSKÁ PRÁCE

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TITLE OF THESIS:

Compact measurement system for calibration of vibration sensors

INSTRUCTION:

1) Make an overview of technical requirements and typical procedures used for secondary calibration of vibration sensors. Focus also on calibration of measuring amplifiers.
2) Design a compact measurement system for calibration of vibration sensors and amplifiers using National Instruments hardware.
3) Design a structure of control software to perform secondary calibration of vibration sensors, vibrometers, calibrators and measuring amplifiers.
4) Assemble a measurement system and develop a computer application in LabVIEW to perform secondary calibration of vibration sensors.
5) Verify the basic functionality of the calibration system and compare results of calibration of a vibration sensor with calibration using SPEKTRA system.

REFERENCE:

[1] Buehn, U. Compendium of vibration calibration. Spektra Schwingungstechnik und Akustik GmbH, Dresden. 2007.

[2] International Standard ISO 16063-21. Methods for the calibration of vibration and shock transducers - Part 21: Vibration calibration by comparison to a reference transducer. 2003.

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ABSTRACT

The objective of this thesis is to design and implement a compact measurement system that would be used for secondary calibration of vibration sensors. Hardware and software of National Instruments was used for development and implementation of the system. NI cDAQ 1974 chassis with analog output card NI 9260 and analog input cards NI 9250 is connected to the PC via USB interface. Graphical user interface allows user to create a calibration specification and run the calibration automatically. Calibration certificate is generated after the calibration run. It includes information about the sensitivity of the device under test, extended uncertainty of the measurement, phase shift and values of total harmonic distortion. The theoretical part contains information about technical requirements for such a calibration system based on norm ISO 16063-21. It also sums up theoretical and practical issues of design of a known calibration system of the company SPEKTRA Schwingungstechnik und Akustik GmbH Dresden, which is used for purposes of primary calibration. The practical part deals with design of the control system and graphical user interface. At the end, results of the secondary calibration are compared to the results of the primary calibration. The result of this thesis is the compact measurement system for secondary calibration of vibration sensors.

KEYWORDS

Secondary calibration,vibration sensors, cDAQ 1974, LabVIEW, NI 9260, NI 9250

ABSTRAKT

Cieľom práce je návrh a vytvorenie kompaktného meracieho systému, ktorý bude slúžiť na sekundárnu kalibráciu vibračných senzorov. Na vývoj a implementáciu bol použitý hardware a software firmy National Instruments. Teoretická časť obsahuje informácie o technických požiadavkách pre kalibračný systém, ktoré vychádzajú z noriem ISO 16063-21. Ďalej zhŕňa teoretické a praktické detaily dizajnu známeho kalibračného systému firmy SPEKTRA Schwingungstechnik und Akustik GmbH Dresden, ktorý sa používa pre účely primárnej kalibrácie. Praktická časť sa zaoberá návrhom riadiaceho systému a grafického užívateľského rozhrania. Výsledky sekundárnej kalibrácie sú na koniec porovnané s výsledkami primárnej kalibrácie. Výsledkom práce je kompaktný merací systém na sekundárnu kalibráciu vibračných senzorov.

KLÍČOVÁ SLOVA

Sekundárna kalibrácia, vibračné senzory, cDAQ 1974, LabVIEW, NI 9260, NI 9250

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ROZŠÍŘENÝ ABSTRAKT

Meranie vibrácií patrí v rámci priemyslu k najfrekventovanejším úlohám. Povaha vybrácií nám môže poskytnúť informáciu o prevádzkovom a technickom stave skúmaného zariadenia. Takáto informácia nám môže pomôcť predpovedať potreby údržby a plánovať opravy či odstávky. Vďaka týmto potrebám dnes existuje množstvo senzorov vibrácií, ktoré sú založené na kontaktnom alebo bezkontaktnom princípe. V tejto práci sa zameriavame na kontaktné senzory vybrácií, založené predovšetkým na piezoelektrickom princípe. Takéto senzory patria k aktívnym senzorom, ktoré vytvárajú elektrický náboj proporcionálne závislý na stlačení piezoelektrického kryštálu a tým pádom závislý na meranom zrýchlení. Senzory pracujú nezávisle na elektrickom poli alebo elektromagnetickom žiarení. Ich odozva je lineárna pri veľkom teplotnom rozsahu, čím sú vhodné na použitie v náročných priemyselných prostrediach. Keďže sú senzory neustále zaťažované a dopyt po ich presnosti rastie s rastúcou precíznosťou výrobných procesov, vzrastajú aj požiadavky na ich kalibráciu. Požiadavky kalibrácie sú definované v norme ISO 16063, ktorá opisuje primárnu aj sekundárnu metódu kalibrácie. Primárna metóda vyžaduje stabilné prostredie s požiadavkami na kvalitu prístrojov a spracovanie dát. Kalibruje sa väčšinou laserovým interferometrom, ktorý zabezpečuje vysokú precíznosť kalibrácie. Sekundárna kalibrácia je založená na porovnaní frekvenčnej odozvy kalibrovaného senzora s referenčným senzorom. Na sekundárnu kalibráciu nie sú preto hardwarové požiadavky také náročné a je ju možné vykonávať s vhodným hardwarom na mieste, kde sú senzory inštalované. Takáto možnosť kalibrácie poskytuje dostatočnú presnosť pri značnej flexibilite meracie procesu. Cieľom práce je navrhnúť a zostrojiť merací systém ktorý by sa využíval na sekundárnu kalibráciu vibračných senzorov tak, aby bol kompaktný a umožňoval jeho prevoz na požadované miesto, kde sa bude kalibrácia vykonávať. Východiskom pre vývoj riešenia budú softwarové a hardwarové platformy National Instruments. Tieto nástroje sú kompaktné, presné a poskytujú prívetivé programovacie prostredie, ktoré umožňuje rýchly vývoj aplikácie. Ako referenčný systém bude slúžiť kalibračný systém SPEKTRA, ktorý sa používa predovšetkým na primárnu kalibráciu senzorov na Ústave automatizace a měřící techniky v Brne. Navrhnutý kompaktný systém sa bude používať ako doplnkový systém k systému Spektra a časti užívateľského prostredia budú napodobňovať spôsob ovládania systému SPEKTRA, aby bol prechod medzi systémami s podobnou funkčnosťou pre užívateľa bezproblémový.

Na vývoj a zhotovenie systému bol použitý hardware a software firmy National Instruments. NI cDAQ 1974 so zásuvnou kartou s analógovými výstupmi NI 9260 a analógovými vstupmi NI 9250 sa pripája k PC pomocou USB. Grafické užívateľské rozhranie umožňuje užívateľovi vytvorenie kalibračnej špecifikácie a au-

tomatické spustenie kalibrácie. Pre spustenie kalibrácie je nutné zadanie všetkých požadovaných informácií ohľadne referenčného senzora, meraného senzora, použitých zosiľovačov a vibračného budiča. Zadané informácie je možné uložiť do XML súboru. Po kalibrácii je vytvorený kalibračný list, ktorý obsahuje informácie o nameranej senzitivite skúmaného senzora, rozšírenej neistote, fázovom posune a hodnotách harmonického skreslenia.

Teoretická časť obsahuje informácie o technických požiadavkách pre kalibračný systém, ktoré vychádzajú z noriem ISO. Ďalej zhŕňa teoretické a praktické detaily dizajnu známeho kalibračného systému firmy SPEKTRA Schwingungstechnik und Akustik GmbH Dresden, ktorý sa používa pre účely primárnej kalibrácie.
Praktická časť sa zaoberá návrhom riadiaceho systému a grafického užívateľského rozhrania. Architektúra programu je založená na mechanizme Queued Message Handler, čo v podstate umožňuje vytvorenie niekoľkých nezávislých podprogramov komunikujúcich pomocou správ. Mechanizmus preto dovoľuje vytvorenie programu, ktorý sa ľahšie udržuje aj pri pridávaní ďalších funkcionalít. V LabVIEW je taktiež možné používanie objektovo-orientovaného programovania, ktoré bolo použité pri zapúzdrení dát kalibračnej špecifikácie a vytvorení hierarchie pre jednotlivé testy, aby bolo možné program jednoduchšie rozširovať o nové kalibračné testy. Samotná kalibrácia pozostáva z niekoľkých častí. Najprv program kontroluje všetky zadané vstupy a overuje, či nebudú presiahnuté limity systému, vibračného budiča alebo senzorov. Následne si systém zistí frekvenčnú charakteristiku vibračného budiča. V prípade, že frekvenčná charakteristika je uložená v pamäti, je možné prejsť priamo ku kalibrácii. Samotná kalibrácia môže prebiehať automaticky, poloautomaticky, alebo v manuálnom režime. Pri každej frekvencii program nastaví na výstup tretinu požadovaného zrýchlenia a kontroluje, či meraná hodnota korešponduje s rozmedzím očakávaných hodnôt. Žiadanú hodnotu ďalej vyreguluje PI regulátor. Po vyregulovaní je regulátor odpojený a na výstupe sa udržiava posledná hodnota, pokým nie je odobratý stanovený počet vzoriek. Dáta sú v oddelenej slučke následne spracovávané. V prípade, že je zapnutá kompenzácia harmonického skreslenia, a jeho hodnoty presiahli dovolenú hranicu, spustí sa režim kompenzácie harmonického skreslenia pokým nie sú nežiadúce zložky signálu vykompenzované. Následne sa dáta uložia a pri automatickom režime sa prejde ku nasledujúcej frekvencii. Pri poloautomatickom režime systém čaká, kým užívateľ povolí generovanie zrýchlenia na nasledujúcej frekvencii. Pri manuálnom režime môže užívateľ zadať žiadané hodnoty frekvencie a zrýchlenia a spustiť kalibráciu s týmito hodnotami. Systém hodnoty skontroluje, a v prípade, že limity nie sú prekročené, prejde ku kalibrácii. V opačnom prípade upozorní používateľa na presiahnutie limitov. Po kalibrácii na všetkých požadovaných frekvenciách je kalibrácia ukončená a program čaká na ďalšie

pokyny užívateľa. Výsledky kalibrácie je možné prehliadať, dopĺňať o podmienky merania a ďalšie informácie, ukladať, alebo použiť pre vyhotovenie kalibračného listu. Kalibračný list obsahuje namerané hodnoty a všetky špecifikované doplňujúce informácie vo formáte dokumentu Microsoft Word, ktorý je možné ďalej upravovať. Výsledky sú doplnené o hodnoty rozšírenej neistoty kalibrácie citlivosti a fázového posunu. Senzitivita je spočítaná nasledujúcim spôsobom:
$\mathrm{S}_{qaDUT} = S_{qaREF} \times \frac{v_{REF}}{v_{DUT}} \times \frac{U_{2DUT}}{U_{2REF}}$

Kde
v_{REF} - zosilenie zosiľovača na strane referenčného snímača
v_{DUT} - zosilenie zosiľovača na strane meraného snímača
U_{2DUT} - výstupné napätie meraného snímača
U_{2REF} - výstupné napätie referenčného senzora
S_{qaDUT} - citlivosť meraného snímača
S_{qaREF} - citlivosť referenčného snímača

Fázový posun je spočítaný ako: $\mathrm{P}_{DUT} = P_{DUT-REF} + P_{REF} - P_{ampDUT}$

Kde
P_{DUT} - fázový posun meraného snímača
$P_{DUT-REF}$ - nameraný fázový rozdiel medzi referenčným a meraným snímačom
P_{REF} - fázový posun referenčného snímača
P_{ampDUT} - fázový posun zosiľovača na strane meraného snímača

Funkčnosť programu bola testovaná na rozsahu 5Hz až 10kHz. Požiadavky normy ISO 16063-21 na neistotu merania citlivosti boli splnené pri rozsahu frekvencií 2 kHz až 10 kHz. Ak sa vstupný rozsah napätia meracej karty využije aspoň na približne 10%, systém by mal splniť požiadavky normy ISO na neistotu citlivosti v celom svojom rozsahu, pri použití vhodných referenčných senzorov a zosiľovačov kalibrovaných v súlade s metódami primárnej kalibrácie. Výsledky a hodnotenie testu sekundárnej kalibrácie sú uvedné v záverečnej kapitole. Súčasťou práce sú aj ukážky kalibračných certifikátov.

DECLARATION

I declare that I have written the Bachelor's Thesis titled "Compact measurement system for calibration of vibration sensors" independently, under the guidance of the advisor and using exclusively the technical references and other sources of information cited in the thesis and listed in the comprehensive bibliography at the end of the thesis.

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Introduction

Vibration measurement belongs today to the most frequent tasks in the industry. The nature of vibrations can give us information about the operating and technical condition of the investigated device. This information can help us predict the need for maintenance and plan repairs or shutdowns. Due to these needs, there is a number of sensors that use contact or non-contact vibration measurement principles. In this work we will focus on contact sensors of vibration, especially on the piezoelectric principle. These sensors belong to the active sensors that produce a small electrical charge which is directly proportional to the compression of the piezoelectric crystal and thus directly proportional to the measured acceleration. These sensors operate independently of the electric field and electromagnetic radiation. Their response is linear for a large temperature range, so they are suitable for use in demanding industrial environments[1]. As these sensors are constantly stressed and their accuracy demands are increasing with improving of manufacturing processes and technology, calibration of such sensors is emphasized. Calibration requirements are defined in ISO 16063, which describes both primary and secondary methods of calibration. Primary methods require a stable environment with high demands on device quality and data processing. It is most often calibrated using laser interferometry, which ensures very precise calibration of the sensors. Secondary calibration is based on comparison of the frequency responses of the calibrated sensors with the reference sensor. For secondary calibration, therefore, the hardware requirements are smaller than for the primary, and can be done directly at the location where the sensors are installed. Such a calibration option provides sufficient accuracy with maximum flexibility of the measurement process. The aim of this work is to design and implement a measurement system that would be used for secondary calibration of the vibration sensors and at the same time would meet the requirements for compactness, so that the system can be easily transferred to the required workplace, where the calibration will be performed. National Instruments tools and software will be the basic starting point for the development of the system. It is because its tools are compact, accurate and provide approachable programming environment, which enables instant and smooth prototyping possibilities. Spectra calibration system will be considered as a reference system, which is currently used for calibration of sensors at the Department of Control and Instrumentation in Brno. The designed compact system will be used as a complementary system to the Spectra, and parts of the graphical user interface will mimic the interface of Spectra, so that switching between the calibration systems can be as smooth as possible.

1 Secondary calibration of vibration sensors

1.1 Definition of secondary calibration

„In secondary calibration or calibration by comparison, the unknown transfer coefficient (sensitivity) of the test object is determined by comparison with the known transfer coefficient of a back-to-back sensor used as a reference standard. In primary calibration according to ISO 16063-11[06], however, the acceleration of the excitation signal is traced back to the wavelength of Helium-Neon laser light by measuring the amplitude of vibration excitation by interferometry. Since this wavelength is well known, it can be used as a material measure of measured vibration displacement. If the frequency of vibration is well known, too, physical excitation quantity $a(t)$ can be determined in this manner with very high precision.“ [1].

1.2 Requirements for apparatus and environmental conditions according to ISO 16063-21

In order to fulfill defined attainable uncertainties, ISO 16063-21 defines two examples of reference transducers and requirements for the apparatus and environmental conditions. We will be comparing sensors under test with Example 1 reference sensor. According to the norm, Example 1 means: „The reference transducer is calibrated by primary means and documented uncertainty. The calibration may be transferred to a working standard for practical reasons. The temperature and other conditions are kept within narrow limits during the comparison calibration as indicated in the appropriate clauses“[7].

The attainable uncertainties (expanded uncertainties calculated using a coverage factor of 2 in accordance with ISO 16063-1) for the two examples are given in Table 1.1. In practice, these limits may be exceeded depending on the uncertainty with which the reference transducer has been calibrated, the response characteristics of the transducers, vibratory characteristics of the exciter and the instrumentation used in the measurement apparatus.

1.2.1 Environmental conditions

The environmental conditions for Example 1 are as follows:
Room temperature (23 ± 5)°C
Relative humidity 75 % max.

Parameter	Example 1	Example 2
Magnitude		
For accelerometers (0.4 Hz to 1000 Hz)	1%	3%
For accelerometers (1000 Hz to 2000 Hz)	2%	5%
For accelerometers (2 kHz to 10 kHz)	3%	10%
For displacement and velocity transducers (20 Hz to 1000 Hz)	4%	6%
Phase shift[a]		
At reference conditions[b] (i.e. the level and frequency at which the reference transducer was calibrated)	1°	3°
Outside reference conditions	2.5°	5°

[a] Phase shift measurement is not mandatory.

[b] Recommended reference conditions are as follows (from ISO 16063-11:1999, Clause 2):

— frequency in hertz: 160, 80, 40, 16 or 8(or angular frequency ω in radians per second: 1000, 500, 250, 100 or 50),

— acceleration in meters per second squared(acceleration amplitude or r.m.s. value): 100, 50, 20, 10, 5, 2 or 1.

NOTE The expanded uncertainties given as examples (e.g. 1%) are based on concrete uncertainty budgets such as given in Annex D of the norm as an example (resulting expanded uncertainty 0.84%).

Tab. 1.1: Attainable uncertainties of magnitude and phase shift of the complex sensitivity[7].

1.2.2 Reference transducer Example 1

The reference transducer should preferably be calibrated together with the amplifier. The transducer shall be calibrated in accordance with suitable primary methods or by comparison against a transducer calibrated in accordance with suitable primary methods (see ISO 16063-11 or other parts) with an expanded uncertainty of 0.5 % (magnitude) and 0.5°(phase shift) at selected reference frequency and acceleration (the uncertainties are those obtained when calculating expanded uncertainties using a coverage factor of 2). Higher uncertainty values are accepted at high and low frequencies.

The reference transducer may be of the so-called back-to-back type meant for direct mounting of the transducer to be calibrated on top of it in a so-called back-to-back configuration. It may also be a transducer with normal mounting provisions used underneath a fixture in line with the transducer to be calibrated. It is not recommended to mount the two transducers side by side as rocking motions will often be present, causing large errors in many circumstances. For calibrators, the reference transducer may be an integral part of a moving element.

1.2.3 Vibration generation equipment

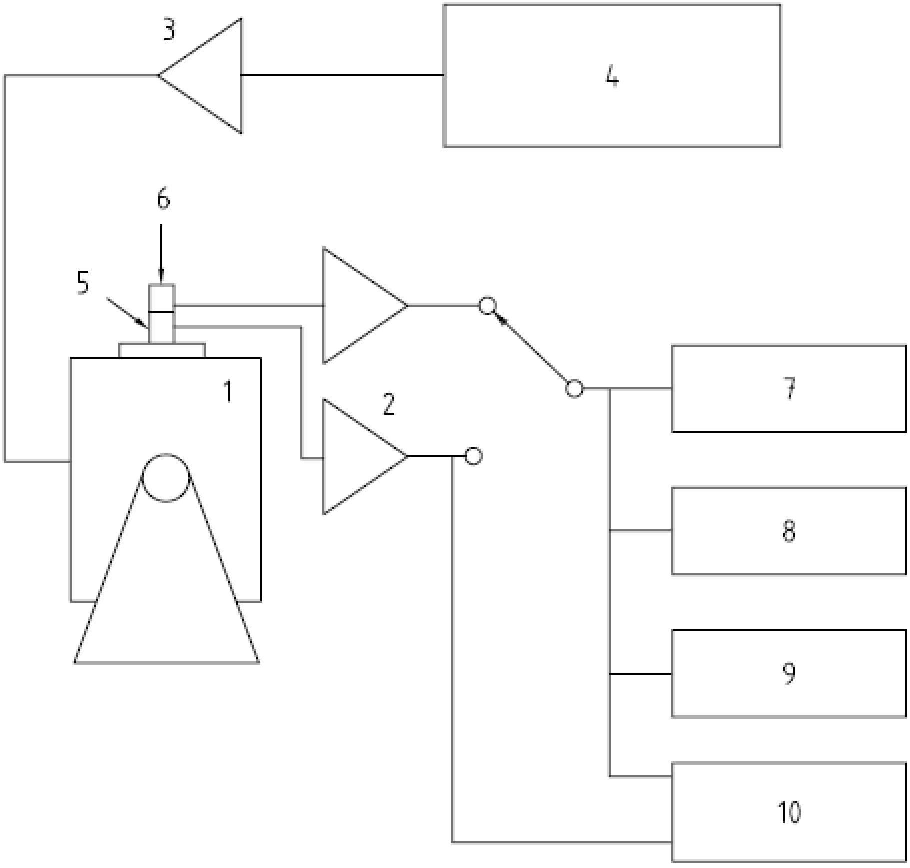
The equipment for generation of vibrations should fulfill the requirements given in Table 1.2.

Parameter	**Unit**	**Example 1**	**Example 2**
Frequency uncertainty	%	≤ 0.1	≤ 0.2
Frequency stability	% of reading over the measurement period	0.1	0.2
Acceleration amplitude stability	% of reading over the measurement period	0.1	0.3
Total harmonic distortion at frequencies $\succ$ 20 Hz	%	≤ 5	≤ 10
Total harmonic distortion over the whole frequency range	%	≤ 10	≤ 20
Transverse, bending and rocking acceleration	%	≤ 10 at $f \leq 1$ kHz ≤ 30 at $f \succ 1$ kHz	
Hum and noise ($f \geq 10\,\text{kHz}$)	dB below full output	≥ 50	≥ 40
Hum and noise ($f \prec 10\,\text{kHz}$)	dB below full output	≥ 20	≥ 10

Tab. 1.2: Vibration generation equipment[7].

1.2.4 Voltmeter

Voltmeter is used to measure effective value of voltage on the output of the signal conditioner. The voltage at the output of the reference sensor and the calibrated sensor is measured in this order, and the voltage at the output of the reference sensor is measured at least twice. This device shall meet the requirements set out in Table 1.3.



Key

1 exciter
2 amplifiers
3 power amplifier
4 frequency generator and indicator
5 reference transducer
6 transducer to be calibrated
7 voltmeter
8 distortion meter for occasional checks
9 oscilloscope for visual inspection (optional)
10 phase meter (optional)

Fig. 1.1: Example of a measuring system for vibration calibration by comparison to a reference transducer[7].

1.3 Process of calibration according to ISO norm 16063-21

1.3.1 Preferred amplitudes and frequencies

Preferably, series of six frequencies must be chosen, each with associated acceleration (amplitude or effective value). Frequencies should evenly cover the sensor range.

a) Acceleration (m/s^2)**:**

1, 2, 5, 10 or its multiples of ten.

b) Frequency:

It can be selected from the range of third octave frequencies listed in the standard (see ISO 266).If broadband signals are used, the required range should be

Parameter	**Unit**	**Example 1**	**Example 2**
Frequency range	Hz	1 - 10 000	1 - 10 000
Maximum deviation from linearity	% data at the maximum difference of the signal level	0.1	0.3
Maximum deviation between two subsequent measurements of the reference sensor	%	0.1	0.3
NOTE The last line describes repeatability of measurement. This comprises more than repeatability of measurement using a voltmeter, but is considered as general requirement.			

Tab. 1.3: Voltmeter parameters [7].

covered by one or several calibrations. The selected values should be preferably the same as those used for calibration of the reference sensors. If the sensor is to be calibrated at other frequencies and other accelerations compared to the reference sensor, properties of the reference sensor should be evaluated at these frequencies and accelerations.

1.3.2 Measurement requirements

If a new set or new sensor is to be calibrated, it is a good practice to repeat the calibration to ensure sufficient repeatability. It is important to ensure that the movement of the cable or the mechanical stress of the sensor base does not affect the results measurements, especially at low frequencies. To evaluate the effects of cable fixation, attachment of the sensor, or both, recorded changes in the measurement results or harmonic distortion can be used. If measured sensitivity or distortion compared to uncertainty calibration does not change significantly, these effects can be neglected. The sensor mounting conditions should be also repeatable. This can be verified by repeatedly mechanically attaching and disconnecting the sensor several times and after each subsequent attachment the sensitivity is measured.

If the above-mentioned tests reveal any deviations which are substantially different compared to the required uncertainty, these deviations should be quantified by making a sufficiently large number of repeated measurements to obtain its good estimate. This estimate must then be included in the final statement about uncertainty. This is especially important if the measurements are not performed on the frequencies and amplitudes on which the reference sensor was measured.

1.3.3 Calibration procedure

The surfaces of the reference sensor (or mount) and the sensor to be calibrated shall be inspected and checked if they contain burrs, etc. and meet the manufacturer's specifications for flatness and specifications referred to in Section 1.2. When attaching the reference sensor and the calibrated sensor, the recommended torque should be applied. Following configurations are used:

1. References with two mounting sides and tested sensor with one mounting side attached to each other as in Figure 1.1
2. fastening system for positioning the sensor above each other in axis.
3. tested sensor is placed on the exciter with a built-in reference sensor.

At frequencies lower than approximately 5 kHz, an appropriate system with known properties can be used to mount the sensors. At higher frequencies, the reference sensor configuration must be used in first or third configuration. Measured is the ratio of the two outputs and, if necessary, the relative phase shift. Sensitivity at the reference frequency is determined first, for accelerometers preferably at 160 Hz (second choice: 80 Hz) and at reference acceleration, for accelerometers preferably at $100 m/s^2$ (additional choices: $10 m/s^2$, $20 m/s^2$ or $50 m/s^2$). Sensitivity at other calibration frequencies and accelerations is determined then-after. The results must be reported in absolute form and or as a relative deviation (in percent or dB) and deviations of degrees from the sensitivity at the reference point. In the case of sensors that are fastened by means of a stud bolt, it is necessary to apply on the surfaces between them and between the exciter and sensors a thin layer of thin oil, wax or Vaseline, especially in the case of calibration at higher frequencies (for details see ISO 5348).

1.4 Typical issues solved in practice

The Chapter 1.4. sums up theoretical and practical issues of design of the well-established calibration system of the company SPEKTRA Schwingungstechnik und Akustik GmbH Dresden[1].

1.4.1 Concept of measurement and sensors

Vibration calibration is a matter of intricate interrelations between mechanical and electrical phenomena and components, always superimposed by disturbing influences. Therefore the uncertainty values are estimated in the range of a few per cent. In vibration calibration, three modes of excitation are currently used: excitation with sinusoidal, shock-type or random signals. Irrespective of the individual design of piezoelectric vibration sensors, all types contain a piezoelectric crystal and a seismic piece of mass. When this piece of mass is moved by exposing it to acceleration, force is created. If this force is applied to the piezoelectric crystal in one way or another, e.g. as compression, flexural or shearing force, this will result in proportional change transfer according to $q(t) \approx F(t)$. A special converter circuit transforms the charge transfer into alternating voltage. Such converter is called charge amplifier and can be available as a stand-alone unit or housed directly in the enclosure of the sensor and fed with an impressed electric current of between 2mA and 20mA. Such a sensor is named ICP® sensor or IEPE Integrated Electronics Piezo Electricals. Next to the piezoelectric vibration sensors, we can find sensors based on other principles as: Piezo-resistive acceleration sensors, capacitive acceleration sensors, Inductive (electrodynamic) acceleration sensors, Servo-sensors, Laser vibrometers and other. The common feature of all those sensors is, that in conjunction with special adapter circuits (signal conditioners) they transform one of the three vibration quantities $a(t)$, $v(t)$ or $s(t)$ into alternating electrical voltage $u(t)$.

1.4.2 Ideal calibration system

If an electrical signal is applied to the electrodynamic vibration exciter, the result of this will be excitation of the coupling surface on the armature in a periodic or singular motion. If the transfer coefficient $Hse = a(f)/U(f)$ of the vibration exciter were precisely known, it would be enough to generate a definite driver signal $U(t)$ in order to obtain a definite acceleration signal $a(t)$. In practice, however, the transfer function of the vibration exciter is dependent on many influence variables (frequency, payload, temperature) and so can be determined and stored only approximately. For this reason, a reference sensor (reference standard) with precisely known characteristics is attached to the exciter head or housed in it, the output voltage of which is used in a control loop to vary the driver signal $U(t)$ such that the required acceleration magnitude a is obtained.

The voltage from the charge-to-voltage converter is amplified by gain factor v, which needs to be selected such that the following analog-to-digital converter is driven in its optimum amplitude range. Allowing for a certain overload margin, this optimum range is:
$Uopt = (0.25 \ldots 0.75)$ full-range value
Following voltage at the input of the analog-to-digital converter is obtained expressed by its RMS value:

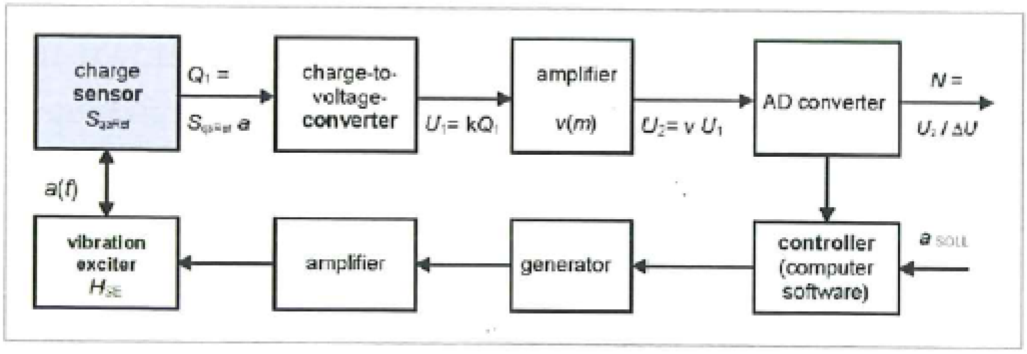


Fig. 1.2: Block diagram of system for the generation of acceleration[1]

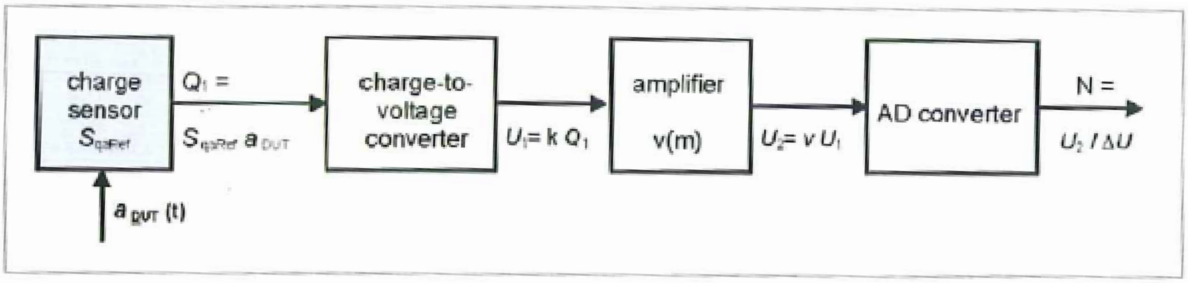


Fig. 1.3: Block diagram of acceleration measurement[1]

$$U_2 = vU_1 = \frac{v}{C} \times Q = \frac{v}{C} \times S_{qa}a \tag{1.1}$$

U_1 - voltage converted from charge
U_2 - output voltage
v - gain factor of the amplifier
C - capacity
S_{qa} - sensitivity of the sensor
a - acceleration

Measured acceleration a_{ist} is compare with reference variable a_{soll} and the driver voltage of the vibration exciter is varied by means of the controller circuit such that a_{soll} and a_{ist} are equal, with the exception of a very small residual offset δa . This offset is dependent on the setting of the controller and can be minimized almost as much as you like. The necessary gain can be calculated from the known values of reference quantity a_{soll} and its frequency. The amplitude can be determined either by means of an rms value detector or by the sine-approximation method. Since the acceleration signal to be measured is mostly unknown with the respect to amplitude and frequency, gain needs be optimized initially using automatic range setting. Frequency, amplitude and, if need be, THD (total harmonic distortion) are determined subsequently using suitable algorithms. Commonly sine-approximation is applied to this end. If we define following quotients:

$$G = \frac{v_{REF}}{v_{DUT}} \tag{1.2}$$

$$R = \frac{U_{2DUT}}{U_{2REF}} \tag{1.3}$$

Where
G - ratio between gain factor reference amplifier vs. DUT amplifier
v_{REF} - gain factor of the reference amplifier
v_{DUT} - gain factor of the DUT amplifier
R - ration between output voltage of the DUT vs. reference sensor
U_{2DUT} - output voltage of the device under test
U_{2REF} - output voltage of the reference sensor

We obtain final sensitivity of the sensor:

$$S_{qaDUT} = S_{qaREF} \times G \times R \tag{1.4}$$

S_{qaDUT} - sensitivity of the device under test

1.4.3 Real calibration system

Signal generation

Since the three vibration quantities a, v and s can be converted into each other and since acceleration is proportional to driving force, the following considerations are focused on the generation of acceleration signals by means of devices that commonly are called acceleration exciters. There are two basic requirements that must be met by the armature of every vibration exciter high stiffness and low weight. In order to generate a harmonic acceleration signal, the armature must be exposed to harmonic force in the preferred direction (axis of free motion). The majority of driving elements in vibration exciters work by the electrodynamic principle. A moving coil, attached to the armature, dives into the cylindrical air gap of a magnetic circuit, which is mostly composed of permanent magnets. Armature should move only with one degree of freedom and the motion should have as little friction as possible and no slip-stick effect. For this reason, a high-quality vibration exciter should have a very low disposition for transverse vibration. The present state of the art is characterized by the application of air suspension or spring suspension in calibration shakers. Such exciters have low disposition to transverse vibration and small Total harmonic distortion compared to spring suspension principle, where Total harmonic distortion is higher especially at higher vibration displacement due to displacement-dependent restoring force of springs. For the sake of frequency analysis, true white noise will be needed. To obtain a signal with a very long repetition period by digital means, the following way is taken: First a very long shift register (e.g. 68 bit) is used to generate binary noise of equal distribution. In this manner repetition periods in the order of a few million years can be achieved. This binary noise is conducted through a form filter designed similar to an FIR filter. With appropriately selected coefficients a1 to a13, white noise with Gaussian distribution of amplitude density is obtained at the output of the summing unit.

Control of vibration quantity

If you feed a vibration exciter with an alternating voltage of constant amplitude, you will find out soon that the acceleration generated is constantly changing. The gradient of change is dependent on the selected frequency and the generated acceleration amplitude. These fluctuations are caused by thermal effects (change of moving coil resistance, frequency-dependent cooling effects etc.). To generate a constant acceleration a PI controller is needed. The algorithm is usually as follows:

$$\mathit{\Delta} U_{TR}(k) = \mathit{\Delta} U_{TR}(k-1) + P \cdot E(k) - (P + I) \cdot E(k-1) \tag{1.5}$$

Where:

$$E(k) = X_{soll} - X_{ist} \approx [a_{soll} - a_{ist}(k)] \tag{1.6}$$

and P - is P component and I - is I component

Pre-distortion of driving signal

AS the spring force follows the Hooks law only for small displacement values, wider displacement will result in a non-linear characteristic which manifests itself in very high total harmonic distortion of the acceleration signal. This is why a sinusoidal driving voltage will generate a really sinusoidal acceleration signal only at low amplitudes. For this reason, the driving signal needs to be pre-distorted such that the overall result is the desired sinusoidal acceleration signal. The algorithm should identify harmonics and generate fundamental wave with the same harmonics opposite in phase. The procedure is repeated by iteration until the actual value of residual total harmonic distortion falls below a specified target value (e.g. 0.5%). For instance, SPEKTRA CS 18 allows user to specify in the test description, under which conditions the process of anti-distortion shall be started.

Measurement using a vibration sensor

The calibration object is pasted or screwed to a back-to-back sensor that is used as a reference standard. The transfer coefficient (sensitivity) of the reference standard must be determined before by the relevant national metrological institute or an accredited calibration laboratory by ascertaining the relation between its electrical output voltage and the acceleration to which its upper coupling surface was exposed. Under these circumstances the acceleration to which the coupling surface is exposed is $a(t) = y(t)/Sn$, where Sn transfer coefficient of reference standard and $y(t)$ alternating charge or voltage, depending on the type of sensor. However the transfer coefficient Sn of the reference standard is dependent on the weight of the attached calibration item. It was also calibrated with a dummy piece of mass in order to simulate the tested sensor. This dependence must be determined accurately, or specified in uncertainty budget.

Signal processing

In a real system, the transfer coefficient Sq is complex and a function of frequency. For reference standard sensors, these characteristics, including uncertainty as a function of frequency, are listed in their calibration reports and entered into the calibration system by appropriate (e.g. electronic) means. With respect to gain, it depends on frequency, settings of the filters and cut-off frequencies and modern system stores the characteristics in the form of a multidimensional vector in order to correct the measured results based on stored vectors. The sequence of samples at the output of the allocated AD converter is corrected and further processing can be performed in two ways: If the phase information can be disregarded, this sequence can be supplied to a digital root-mean-square calculator operating by the conventional principle, maybe supplemented by a digital narrow-band filter and a band-stop filter. In this manner even very low signals can be processed with small uncertainty. If the angle of phase difference is of further interest, the sequence of samples must be processed using sine approximation.

Environmental and any other disturbing variables

Effect of temperature

As a rule, vibration sensors are calibrated in an air-conditioned room, e.g. at 23 °C $\pm 2K$. If the vibration sensor is used later at some other temperature, its transfer coefficient must be corrected. Another unpleasant feature is called pyro-electric effect. This effect makes itself felt in the form of a transient output signal of high amplitude when there is a jump in environmental temperature (e.g. by draught). If this influence cannot be avoided, calibration must be performed under a protective hood.

Effect of transverse vibration

In modern calibration systems, the test item is first tested with regard to its aptitude to be calibrated prior to the calibration run proper. To this end the entire frequency range is scanned relatively fast with a sliding frequency signal sweep. If the test object is intact and thus ready for calibration, it will show a response curve similar to the one in Figure, since any possibly existing transverse resonances are unable to build up to full size.

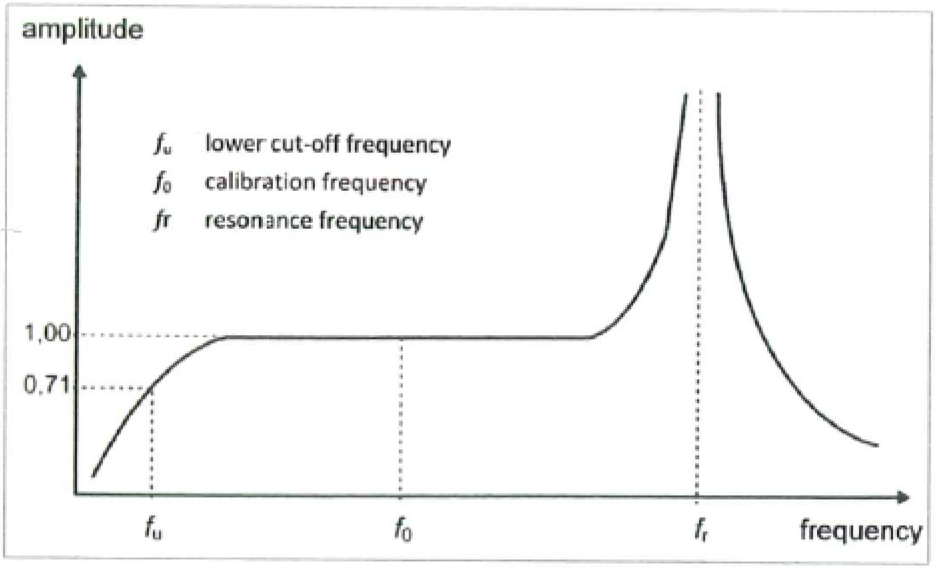


Fig. 1.4: Frequency response of vibration sensor [1]

Such a response would be measured in the vicinity of the transverse measurement.

Fig. 1.5: Typical curve of transfer coefficient in the vicinity of transverse resonant frequency [1]

Base strain

If the coupling surface of a vibration sensor is somehow mechanically deformed, this deformation will have an effect on the crystal and the seismic piece of mass and so generate a disturbing signal that superimposes on the wanted signal. This disturbing effect is highly pronounced particularly below 500 Hz, as vibration displacement is much wider at low frequencies. This is a bias error that should be compensated for by way of calculation.

Effect of magnetic field can be also observed at frequencies around 50Hz. The foreign magnetic field can induce foreign voltage which can be converted into a vibration quantity.

Effect of gravitation may be important for high-sensitivity vibration sensors with a low cut-off frequency (0Hz in an extreme case). Static acceleration signal $g_n \cdot \cos\alpha$ is added where is the angle between the direction of gravitation and the direction of acceleration excitation and is gravitational acceleration of approx. $9.81m/s^2$.

Effect of payload

The following graphs illustrate the influence of the payload on the sensitivity of the reference sensor.

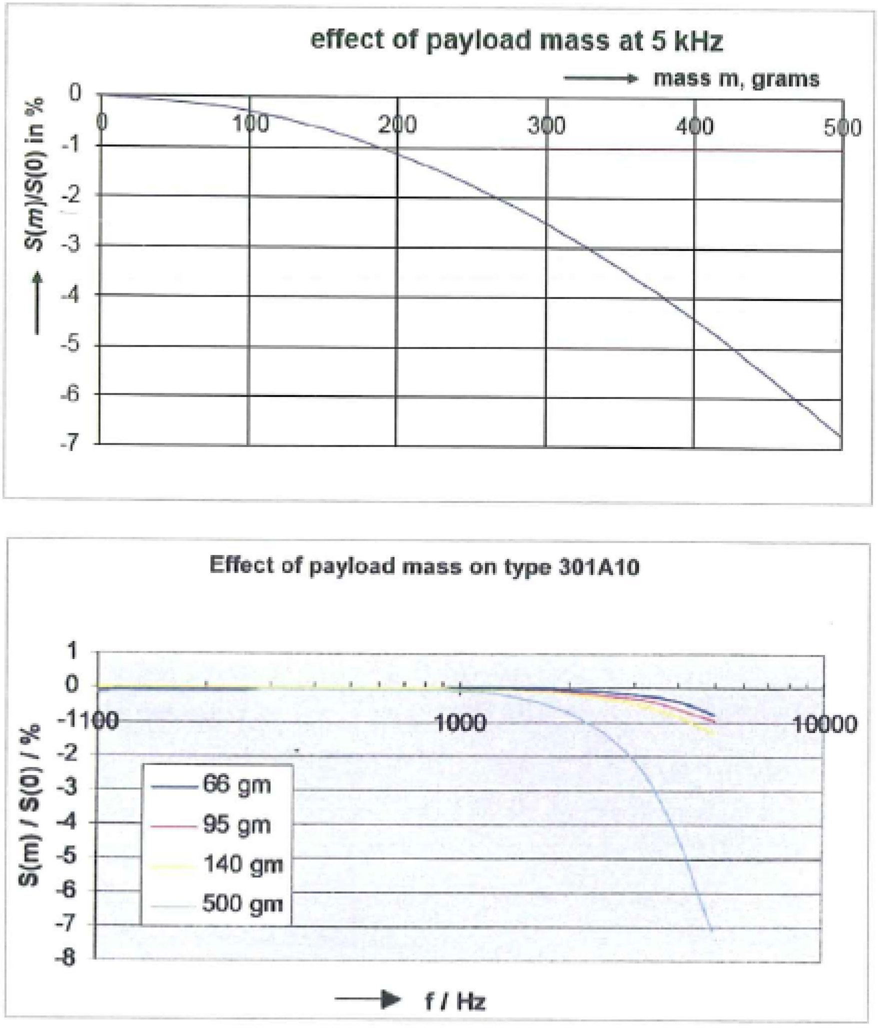


Fig. 1.6: Effect of payload mass [1]

If in a calibration laboratory only items shall be calibrated the weights of which are roughly identical, it is recommended to calibrate the back-to-back sensor used as a reference standard with a payload equal to this mass. Small differences between the weights of different calibration item can be taken into account by specifying an allowance to uncertainty. On the other hand, if the range of products is widespread, the effect of the payload mass on the sensitivity of the back-to-back sensor used needs to be determined by interferometric measurement.

Effect of mounting – only modes screwing and gluing are serious possibilities for calibration purposes.

Cable routing should be considered, because bad routing will increase the standard deviation.

Vibration isolation – any vibration exciter used for calibration should be attached to a compact block, the weight of which should be at least 2000 times the mass that is moved in the calibration process. And the resonance frequency of the compact block should be sufficiently far below the lowest calibration frequency.

Calibration of signal conditioners

In this case the calibration task is to generate the quantity generated by the primary transducer by electrical means and determine the generally complex transfer coefficient of the conditioned as a function of frequency. To calibrate a module of this kind, a calibration system must be able to generate definite alternating charges and alternating voltages and to measure voltage. When ICP power supply unites shall be calibrated, the system must also be able to absorb the dc current produced by these units, i.e. it must be equipped with a current sink. Before the calibration following things should be also specified:

- Allocation of channels
- Selection of frequencies and voltages of the excitation quantity
- Specification of the reference frequency, e.g. 160 Hz
- Selection a reference capacitor (100 pF, 1nF)

Determination of measurement uncertainty

The measurement value is attributed to the measurement item by comparison with a quantity the value of which is known. In this approach, the issue of accuracy can be focused on the following two questions:

1. How accurate is the process of comparison?
2. How accurate is the standard used for comparison?

The complete result of every measurement is a couple of values consisting of:
-The value attributed to the measurement
-Measurement uncertainty attributed to the value

Calibration certificate

Every accredited calibration laboratory is required to keep to certain rules formatting when issuing a calibration certificate, whereas a non-accredited calibration laboratory needs not to do so. For this reason every CS18 Calibration system by SPEKTRA enables the user to export his data in Excel format.

2 Design of a compact measurement system

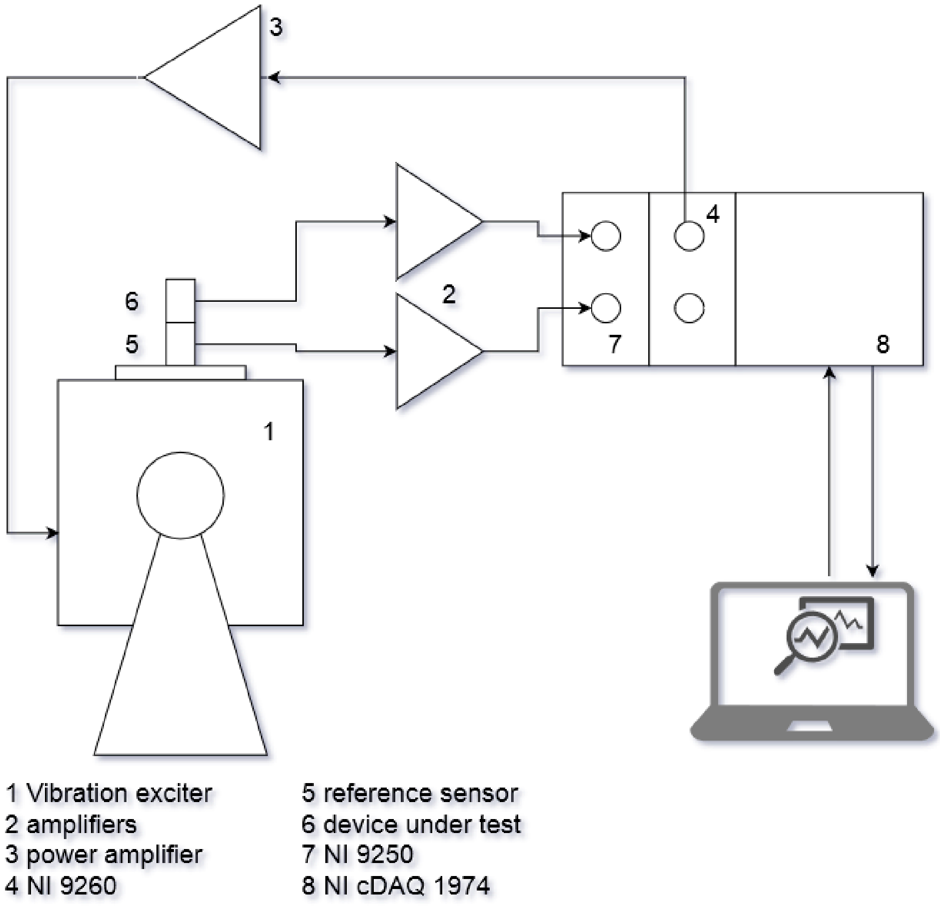


Fig. 2.1: Block diagram of the designed system

2.1 NI-Compact DAQ Platform

NI-CompactDAQ belongs to large family of modular hardware components which provide a great deal of flexibility if combined with I/O cards and LabVIEW programing environment. The chassis can be connected to the PC through USB. It provides space for four I/O modules which provide direct sensor connectivity. For our application two slots will be sufficient for connection of one input and one output card.

Fig. 2.2: NI cDAQ-1974 [8]

2.2 NI-9260 Output Card

NI-9260 is a 2-channel Delta-Sigma analog output module with a $51.2kS/s$ update rate, 24-bit resolution and 3 Vrms output range. The card features ±30 V over-voltage protection and short circuit protection for safe deployment. Connectivity is possible through BNC cable. The output stage of the NI 9260 with BNC is pseudo-differential. AO- is terminated using a 50 Ohm resistor to GND.

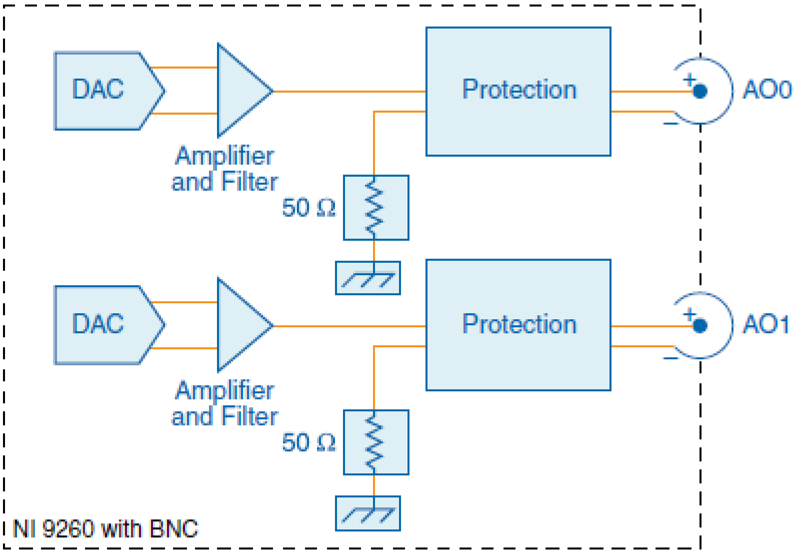


Fig. 2.3: Output circuits of NI-9260 [8]

The frequency of a master time base (f_m) controls the data rate (f_s) of the NI 9260. The NI 9260 includes an internal master time base with a frequency of 13.1072 MHz, but the module can accept an external master time base or export its own master time base. The following equation provides the available data rates of the NI 9260:

$$f_s = \frac{f_M \div 256}{n} \tag{2.1}$$

n - any integer from 1 to 31.

Measurement Conditions Calibrated	**Percent of Reading (Gain Error)**	**Percent of Range (Offset Error)**
Maximum (-40 °C to 70 °C)	±0.6%, ±0.05 dB	±0.7%, ±30 mV
Typical (25 °C, ± 5 °C)	±0.03%, ±0.0025 dB	±0.025%, ±1 mV

Tab. 2.1: Gain and offset error of NI-9260 [8].

2.3 Signal amplifier for vibration shaker

TYPE 2718 power amplifier has power output capability of 75 VA. It is specially designed for small vibration exciters. It has low distortion over wide frequency range.[9] The signal amplifier data sheet records following parameters:
Current Limiting Max. 5A for Vibration Exciter Type 4809
Frequency response 10Hz to 20 kHz (±0.5dB)
Harmonic distortion less than 0.2% (20Hz to 20 kHz) at full output capacity
Multifunction Display Current, Voltage, RMS, read-out
Accuracy ±3%, Adjustable ±1digit, 50 Hz to 20 kHz
Weight: 11Kg

2.4 Vibration exciter type 4809

Vibration exciter is suitable for accelerometer calibration and vibration testing of small objects. Most important details from its data sheet, which will influence definition of the test description are:
Force rating 45 N sine peak, 60 N with air cooling
Frequency range: 10 Hz to 20 kHz
First axial resonance: 20 kHz
Maximum displacement: 8 mm peak-to-peak
Maximum bare table acceleration: 736 m/s^2 (75g), 981 m/s^2 with air cooling

Max. Velocity: 1.65 m/s peak
Low cross motion and low distortion
Maximum Input Current: 5A RMS, 7A RMS with forced air cooling
Weight: 8.3 kg

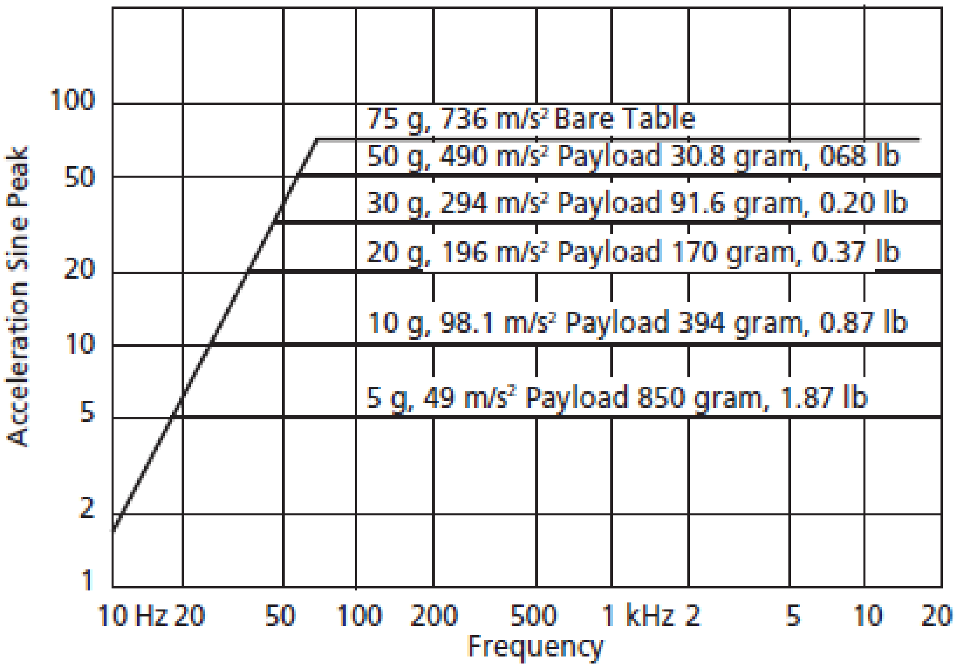


Fig. 2.4: Sine performance curves for Vibration Exciter Type 4809 operating without assisted cooling [9]

2.5 Vibration sensor

The system is designed to work with vibration sensors based on charge output or ICP sensors. Sensors with charge output have specified gains in $pC/m/s^2$ and should be connected to signal conditioner before connecting to the measurement card. If the signal conditioner does not have external excitation source, excitation should be provided by measurement card by specifying the mode of the sensor to CHA. ICP sensors have specified gains in $mV/m/s^2$ and should be connected to the measurement card directly. Excitation should be provided by the measurement card by specifying the mode of the sensor to ICP. In the case, that acceleration sensor with charge output is connected to signal conditioner with external excitation source, the mode of the sensors should be specified to DIR. The testing was realized with reference Accelerometer PCB J353B01
Frequency range: 5Hz-20kHz
Sensitivity: 2,0138 $mV/m/s^2$

Measurement uncertainty:
5 Hz to <20 Hz 0.5% / 0.5°
20 Hz to 1 kHz 0.3% / 0.5°
> 1 kHz to 5 kHz 0.5% / 0.5°
> 5 kHz to 10 kHz 1.0% / 1.0°
The specified values are the extended measurement uncertainties obtained by multiplying the standard measurement uncertainties by extension factor k = 2. The values of the measuring quantity fall into the assigned intervals with a probability of 95%.

2.6 Signal conditioner

The system is designed to work with signal conditioners with specified gains in mV/pC. The testing was realized with Charge amplifier M68D1 with 50kHz low pass filter and 0.1Hz high pass filter, gain 10 mV/pC.

2.7 NI-9250 Input Card

The NI 9250 with BNC is a 2-channel Delta-Sigma analog input module with a $102.4kS/s$ update rate, 24-bit resolution, and ±5V input range. The card incorporates both a TEDS input path and IEPE signal excitation source that can be turned on and off. The frequency of a master time base (f_m) controls the data rate (f_s) of the NI 9250 with BNC. The card includes an internal master time base with a frequency of 13.1072 MHz.

$$f_s = \frac{f_M}{4 \times a \times b} \tag{2.2}$$

where a is the decimation rate (32, 64, 128, 256, 512, 1024), and b is the clock divider (integer between 1 and 12). f_M/b must be greater or equal than 1 MHz.

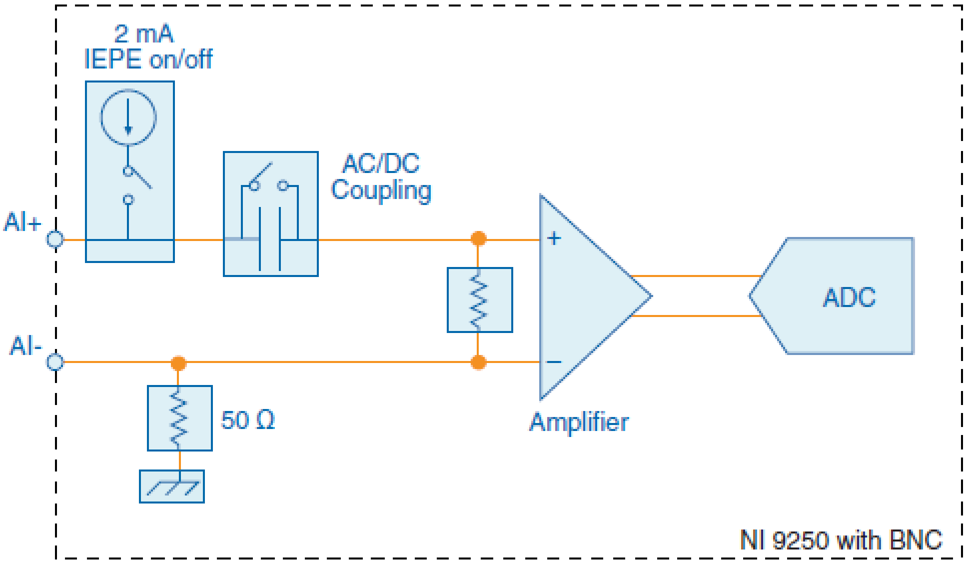


Fig. 2.5: Input circuits of NI-9250 [8]

Input delay – $34/f_s + 2.7$micro seconds

Input impedance AI+ to chassis 2MOhm || 280 pF

AI- to chassis 50 Ω

Input voltage range minimum ± 5 Vpk

IPEP excitation current minimum 2 mA

IEPE excitation noise 70nArms at $102.4kS/s$

Offset error (AC coupling) ± 0.025 %

Stability of accuracy

Gain drift 5.5 ppm/$°C$

Offset drift 33μV/řC

Measurement Conditions	**Percent of Reading (Gain Error)**	**Percent of Range (Offset Error)**
Maximum (-40 °C to 70 °C)	±0.20%	±0.15%
Typical (23 °C, ± 5 °C)	±0.05%	±0.025%

Tab. 2.2: Accuracy in DC Coupling NI 9250 [8].

Data Rate (Ss)	**ADC Decimation Ratio)**	**AC or DC Coupling(µVrms)**	**IEPE Mode with AC Coupling(µVrms)**
102.400	32	9.9	13.2
51.200	64	6.7	8.7

Tab. 2.3: Idle Channel Noise NI 9250 [8].

3 Structure of the control software

3.1 Setting of the measurement and user interface

3.1.1 Program requirements

Programing of a graphical user interface in LabVIEW is most of the time an integral part of the code writing process. Every Virtual Instrument (VI) in LabVIEW has a Front Panel which is essentially a graphical user interface and a Block Diagram which provides space for definition of graphically defined algorithm, how respective controls and indicators should interact. LabVIEW also defines several structures and programming patterns which can be useful for implementation of different functionalities. As mentioned in the introduction, the application should be capable to operate in several modes, what we typically encounter in current calibration systems. For example sensor calibration mode, vibration calibration mode, calibration of signal conditioners and other modes. It is possible, that we will be most likely willing to add some modes of operation to our system in the future. That brings the first requirement of the modularity. Our application will be also combining several functionalities, as log file writing, GUI updates, the signal generation and acquisition part, while some of the code may be running in separate loops and in parallel as well. The user should dynamically change the graphical content of the interface according to respective mode and required function. We will therefore need to find such a design and patterns that will allow us to create such a flexible, modular and responsive application and user interface.

3.1.2 LabVIEW Object-oriented programing

One of the good ways to build a scalable and extensible system is to take advantage of using LabVIEW Objective programming. Using classes would first of all provide us with the advantages of encapsulation, what means that our data will be private, and the access to them will be defined through methods. Secondly we can take advantage of inheritance, which at the end makes the code more readable and easily extendable. The hierarchy of classes can look as follows:

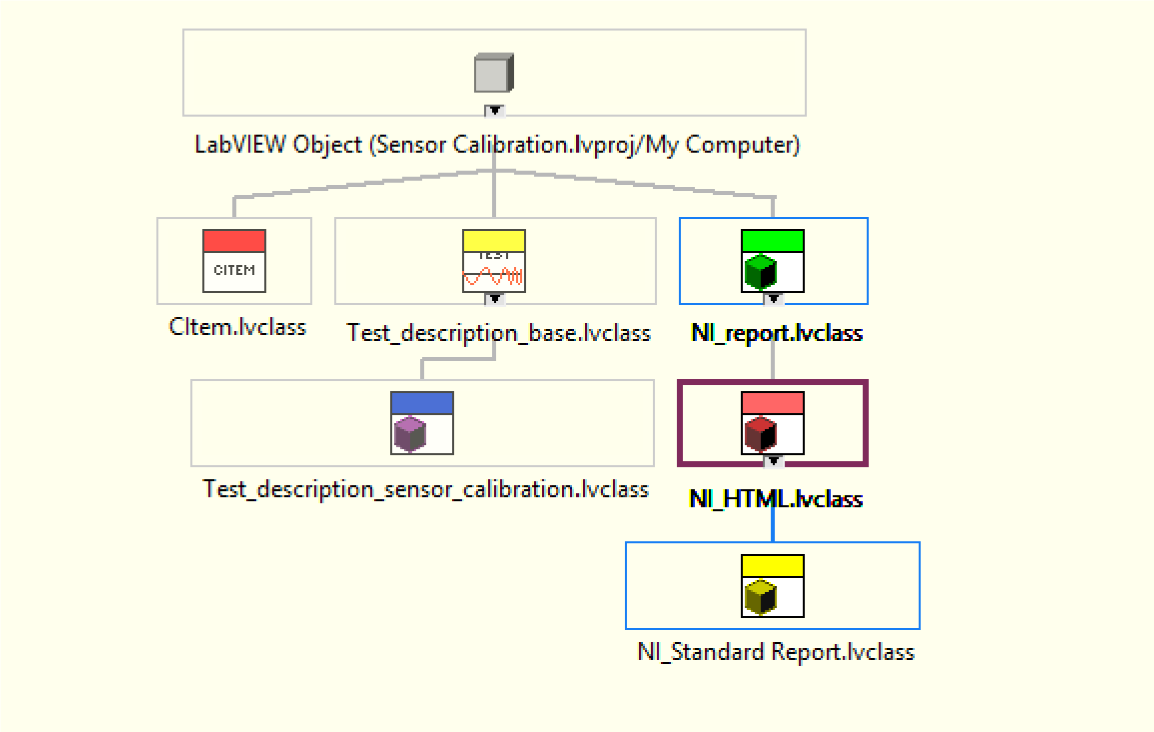


Fig. 3.1: Class hierarchy

Ideal starting point for encapsulation is the Test description, which propagates throughout the whole application and influences each aspect of the calibration process. As the test description varies for different modes of operation, we can introduce base class with some common properties and several child classes, each for different mode of operation. The base class will contain data, which are shared by all child classes, especially calibration frequencies and accelerations. Each calibration point - combination of frequency and acceleration can also form a class which has several advantages. Such a class called Calibration Item CItem, can perform calculations on its data with private methods, and objects of this class can be stored in array in the Test description class.
The test description will contain several method as:
Queue Up method which queues up new calibration item
Remove method which removes calibration item
Read test description method which returns the table with all calibration items
Set DAQmx method which provides settings for data generation and acquisition sub VI
Report specification method which provides data about the test description during generation of the calibration report.

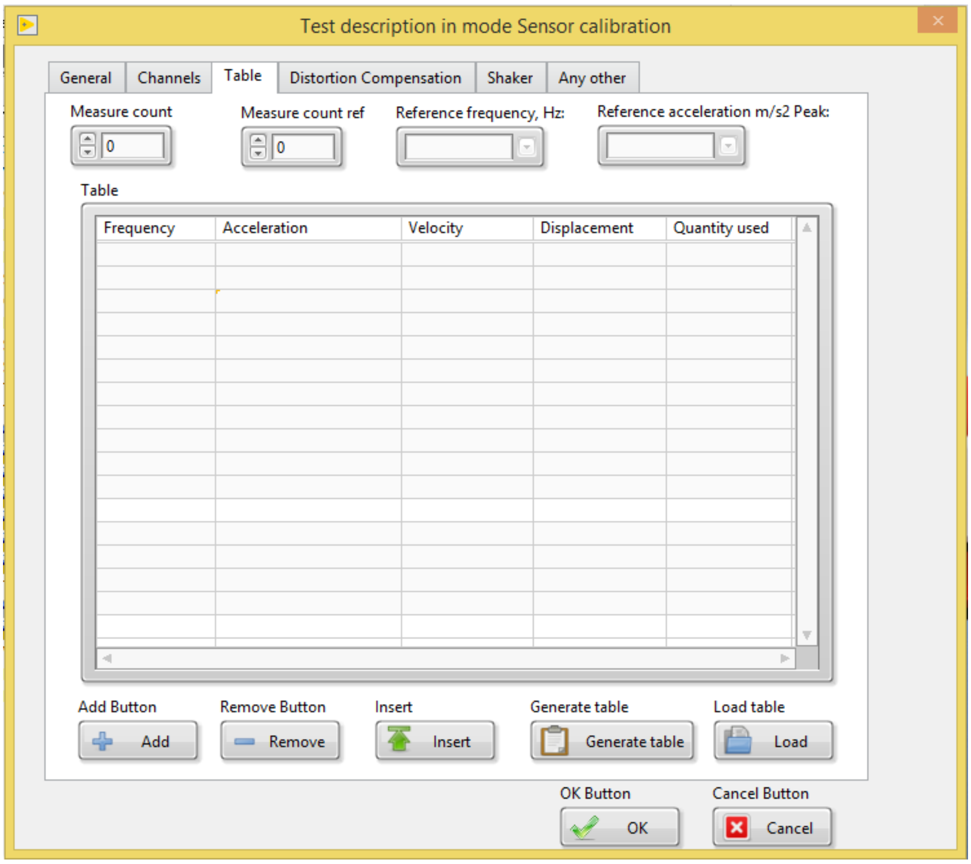
3.1.3 Queued Message Handler

Due to the demands on modularity and complexity of the system, basic state machine with event structure may not satisfy all the requirements of the system. Especially during the calibration process, the application would wait long time before the calibration run finishes. We will have to distribute the code to several parallel loops, so that we can concurrently detect users events, run calibration or define new test description. At the same time, loops should be able to communicate between each other and exchange data. Suitable option for addressing this issue would be use of Queued Message Handler template architecture.[8] It consists basically from two loops Event handling loop and message handling loop. More loops can be added according to specific application. The event handling loops processes user inputs and issues messages, which are then processed in the message handling loop. Message handling loop controls other loops and divide the commands to other loops containing blocks of code. It therefore serves as a communication hub for all other programs around.

3.2 Setting of the measurement and user interface

3.2.1 Calibration of vibration sensors by method of comparison

After entering the sensor calibration mode, test description must be specified at first. By clicking on the button „New description“, we can enter test specification in a new dialogue window.



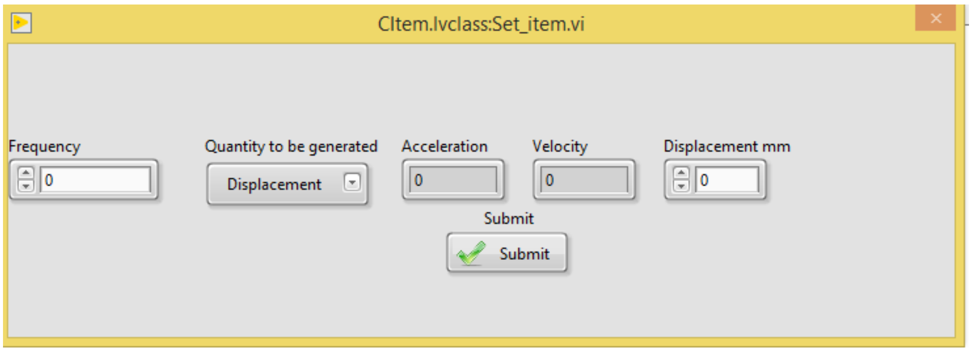
Measure count 0

Measure count ref 0

Fig. 3.2: Dialogue table of the Test Description

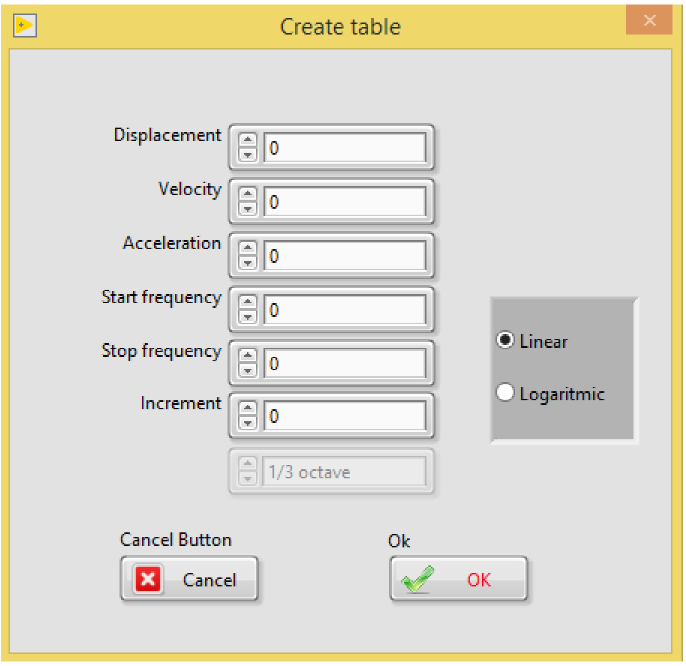
The calibration run always starts with the reference frequency. If not specified otherwise, the systems uses three complete sine periods to form a data-set to determine the measured quantities. The measure count specifies, how many data-sets shall be averaged at each frequency. Further required frequencies can be specified on the table by using Add, Remove and Insert buttons. Delete button erases the whole table. Add and Insert buttons will lead to another window, which belongs to the Calibration Item class. Frequency and one of the quantities DisplacementAcceleration should be specified. The dialogue window calculates all other quantities. The window is programmed to set the last value after reopening, what can be useful for the user.

In this manner whole table can be specified. The second option for definition of the calibration quantities is using automatic table generation, which serves for linear or logarithmic distribution of frequencies with specified peak values of acceleration, velocity and displacement. The third option is loading some previously saved descriptions from the file.



Frequency: 0
Quantity to be generated: Displacement
Acceleration: 0
Velocity: 0
Displacement mm: 0

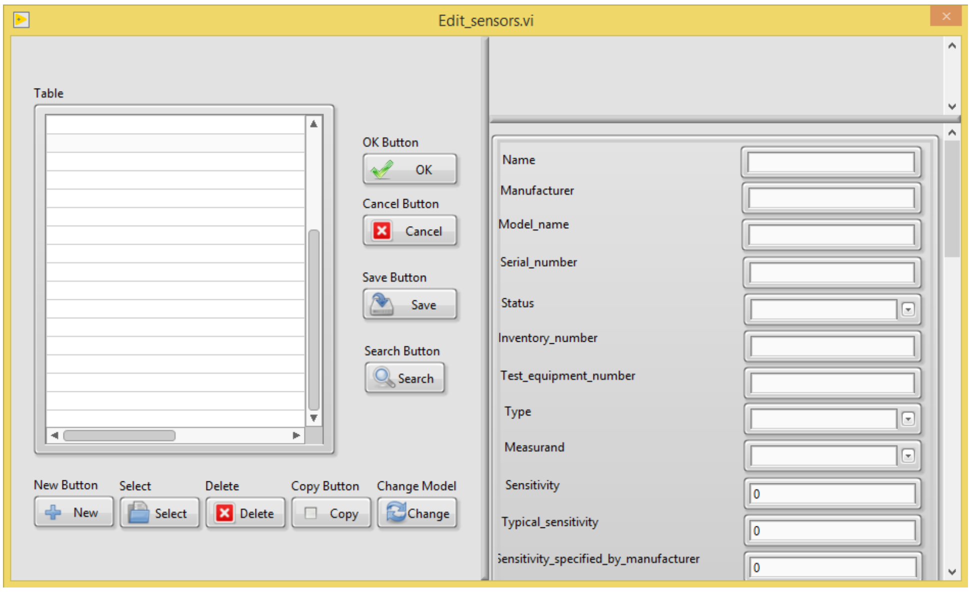
Fig. 3.3: Dialogue table for definition of the calibration frequency and other quantities.



Displacement: 0
Velocity: 0
Acceleration: 0
Start frequency: 0
Stop frequency: 0
Increment: 0
1/3 octave
● Linear
○ Logaritmic

Fig. 3.4: Dialogue table for automatic creation of the Test description

On the next tabs of the Test description we can define all necessary components of the measurement system. The most crucial settings are selection of the reference and DUT sensor, signal conditioners and vibration exciter. Initially we should select a type of sensor currently connected to the system. If such type does not exist yet, we should create new specification by hitting the button New. We are asked to fill in all required fields, which include: Name, Manufacturer, Type, Serial Number, Type of signal conditioner, Measuring quantity, Weight. Next to specification of the required fields, other ancillary information can be added as well. For the reference sensor following information should be provided as well: Sensitivity, Transfer function, Maximum payload, Date of last calibration, Date of next calibration, Calibration interval in days, Number of calibration certificate, Calibration laboratory, Minimum and maximum frequency and maximum frequency for sweep.



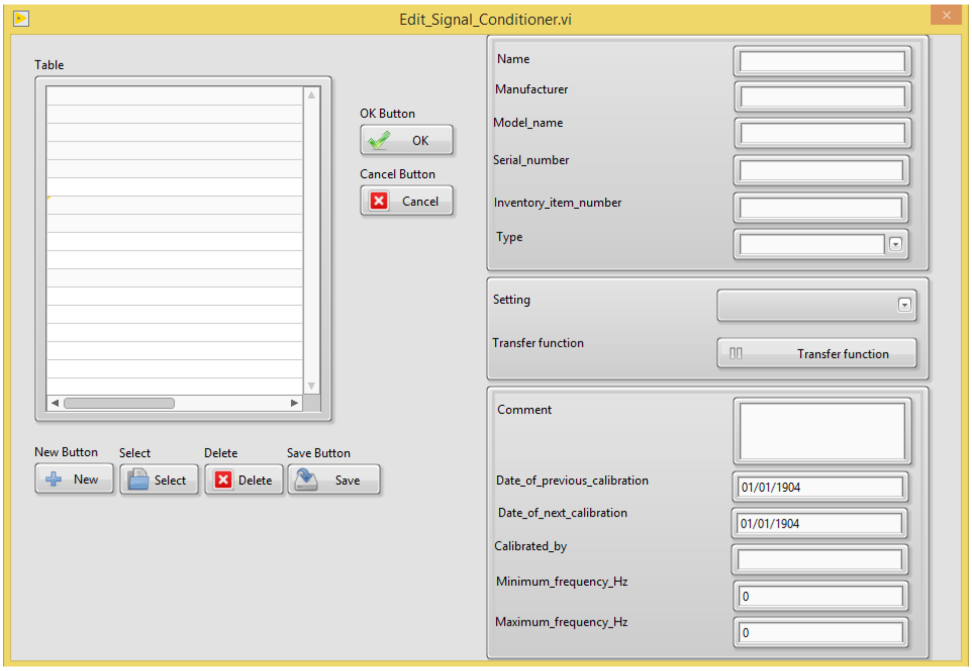
Sensitivity 0

Typical_sensitivity 0

Sensitivity_specified_by_manufacturer 0

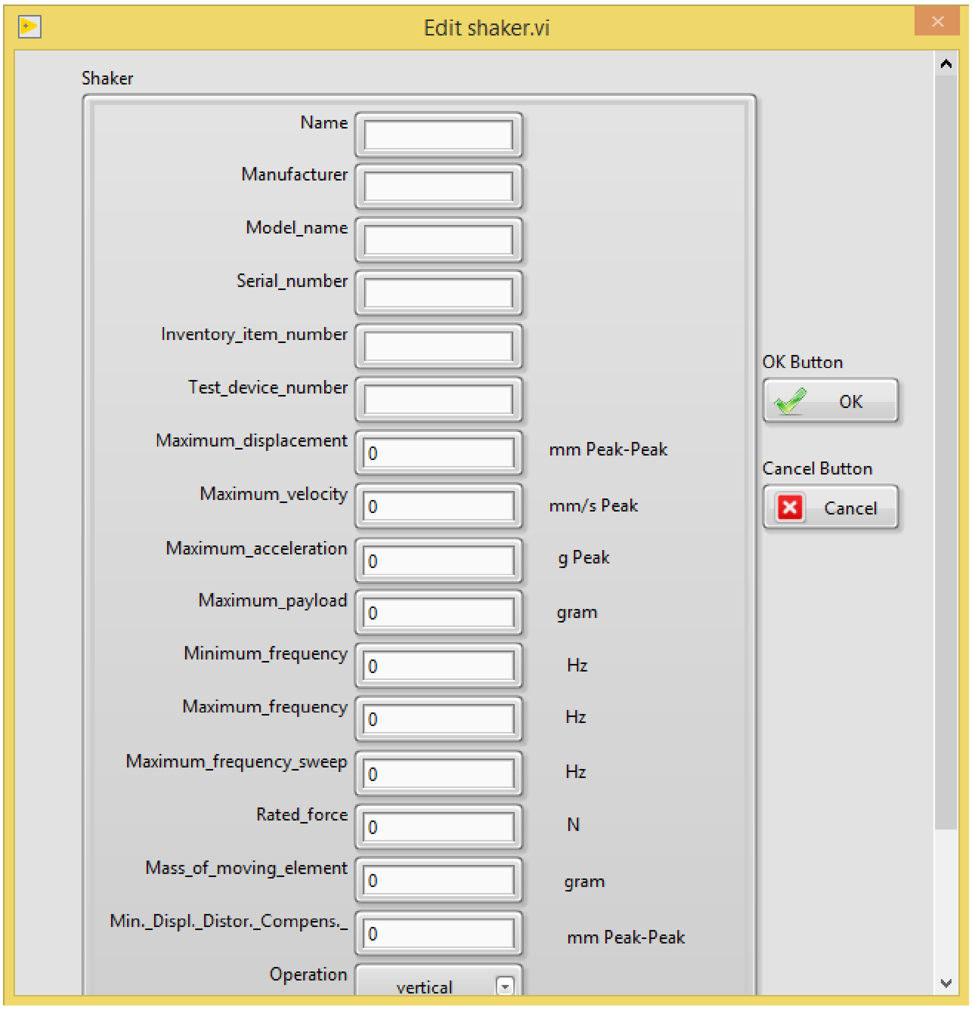
Fig. 3.5: Dialogue table for sensor selection

If signal conditioner is applied, we should select the required type from the list or specify new signal conditioner and its transfer function. In the same way vibration exciter should be selected or specified. The required information include Name, Manufacturer, Model name, Serial number, Maximum displacement, Maximum velocity, Maximum acceleration, Maximum payload, Minimum and maximum frequencies, Maximum frequency for sweep, Rated force, Mass of moving element.



Name
Manufacturer
Model_name
Serial_number
Inventory_item_number
Type
Comment
Date_of_previous_calibration 01/01/1904
Date_of_next_calibration 01/01/1904
Calibrated_by
Minimum_frequency_Hz 0
Maximum_frequency_Hz 0

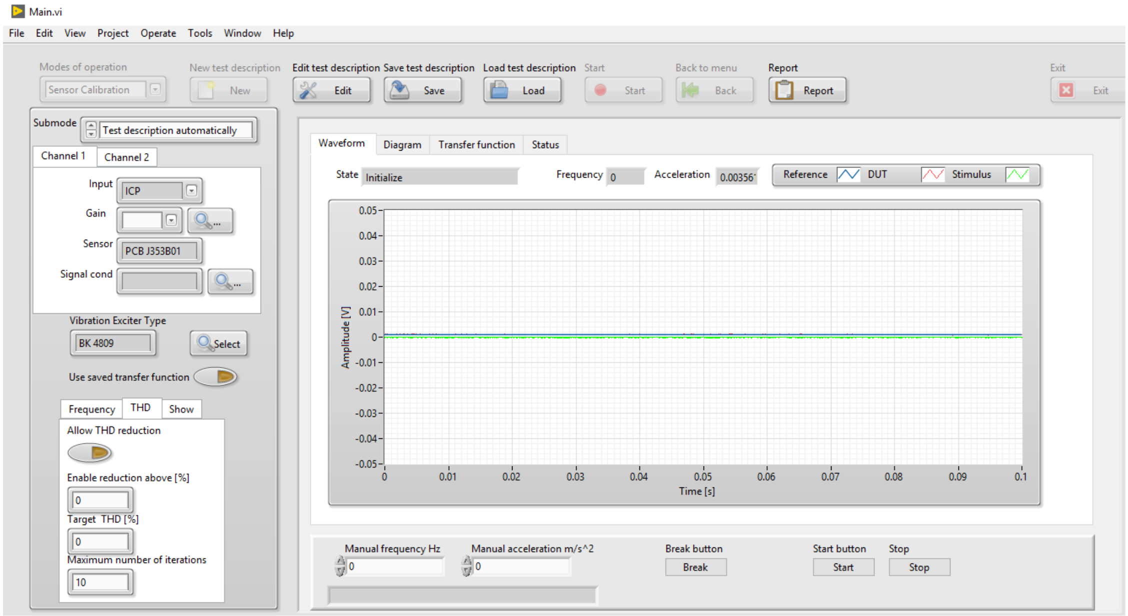
Fig. 3.6: Dialogue table for selection of a signal conditioner



Name
Manufacturer
Model_name
Serial_number
Inventory_item_number
Test_device_number
Maximum_displacement 0 mm Peak-Peak
Maximum_velocity 0 mm/s Peak
Maximum_acceleration 0 g Peak
Maximum_payload 0 gram
Minimum_frequency 0 Hz
Maximum_frequency 0 Hz
Maximum_frequency_sweep 0 Hz
Rated_force 0 N
Mass_of_moving_element 0 gram
Min._Displ._Distor._Compens._ 0 mm Peak-Peak
Operation vertical

Fig. 3.7: Dialogue table for selection of a shaker

After these steps and further settings of the sensors, signal conditioner, shaker and other display settings, test description can be stored for the needs of future calibrations. We can see all settings on the front panel with calibration frequencies. When we hit the start button, the application checks for correctness of the settings and starts the calibration process.



Modes of operation: Sensor Calibration
Submode: Test description automatically
Input: ICP
Gain:
Sensor: PCB J353B01
Signal cond:
Vibration Exciter Type: BK 4809
Use saved transfer function
State: Initialize
Frequency: 0
Acceleration: 0.00356
Allow THD reduction
Enable reduction above [%]: 0
Target THD [%]: 0
Maximum number of iterations: 10
Manual frequency Hz: 0
Manual acceleration m/s^2: 0

Fig. 3.8: Calibration process control window

3.3 Measurement system software

3.3.1 Control of signal generation and acquisition

Generation and acquisition are divided into two different tasks. Each task is configured separately based on information from the Task description. In mode sensor calibration both task have statically defined few properties of the measurement as:

Generation card:

Physical channel the setting of the hardware is not expected to vary, therefore channels can be specified statically. The generation card will use one output channel for the control of signal generation.

Minimum and maximum generation voltage is restricted to ±1V in order to provide suitable level of voltage for the amplifier.

Regeneration mode - is set to not allow regeneration, because data for generation are specified in each cycle when the buffer is updated

Sample clock source On board clock

Sample rate set to the maximum rate of the card

Number of samples one tenth of the sample rate

Sample mode Continuous samples

Acquisition card:

Physical channel - The acquisition card uses also one channel, but it will be pos-

sible to use more channels for acquisition of signal from more sensors for parallel calibration of several sensors if such a requirement arises in future.
Minimum and maximum input voltage set to the range of expected values from the sensor amplified by the signal conditioner
Sample clock source On board clock
Sample rate same rate as the generation card
Number of samples one tenth of the sample rate
Sample mode Continuous samples

Other properties of the measurement system are set dynamically according to the test description: Number of calibration frequencies, Frequency values, Acceleration values, Measure count indicating number of values to be averaged.
The control program is organized in a state machine. The states are reflecting different modes in which the shaker should operate. It needs to continuously increase and decrease generated amplitudes, control exceeding of output limits, regulate the acceleration amplitude, harvest samples for the further processing and analysis, compensate THD, wait on further commands and many other necessary states.

3.3.2 Setting of PI controller

In design of the regulator following issues have to be taken into consideration. Controller does not need to be designed to control each point of the signal. It will rather evaluate the output value in blocks of data. Frequencies higher than 10 Hz can be recognized in the block with length of 0.1s, what is the update length of the generation card. For frequencies below 10Hz, data should be analyzed from several data blocks of the length 0.1s, so that the fundamental frequency can be recognized correctly. The blocks are then processed to always contain integer multiple of signal periods, so that the amplitude would not be influenced by the changes of frequency. Resonance frequency of the shaker together with the sensor varies according to mass of the sensor. Such a discrepancies can be handled by PI regulator itself, however it is possible to detect the frequency response of the system and implement an inverse filter on generated signal in order to limit the work of the PI controller to minor corrections of the signal. The gain of the PI controller is therefore calculated from the frequency response of the shaker and the sensor. The controller algorithm should use a band-pass filter to suppress potential noise of upper harmonics energies from the measured signal.[6] For this purpose we use LabVIEW function based on frequency analysis, which separates only the amplitude of the fundamental frequency. As the reference sensor can be changed and thus the gain of the closed loop will be influenced we should consider how to prepare the system for such changes. One

way would be to try the heuristic method of Ziegler-Nichols and determine the ultimate gain and oscillation period. Then the controller can be set by multiplication of the ultimate gain and oscillation period by the empirically given constants for the no overshoot transition from the Ziegler-Nichols tuning rules. Avoiding of any overshoot should help keeping the durability of the vibration shaker. The ultimate gain was found as an inverse of the combined gain of the sensor and the vibration shaker. The oscillation period was roughly 0.5s for any frequency. It is therefore crucial to determine the frequency response of the vibration shaker in order to specify constants for the controller for each frequency. According to Ziegler-Nichols for no overshoot, following relations were applied:
Kp = Ku/5 Ki=2/5 * Ku/Tu
After calculation of the oscillation period, the transition was still showing some overshoot, so we decreased the multiplier in the Ki part and the controller is set according to following rules:
Kp = Ku/5 Ki=0.4* Ku/Tu
Where:
Kp - is proportional gain
Ki - is integral gain
The system is fragile and many components can cause a fail during the test. Therefore the controller has to monitor abnormal changes in the input signal and output signal and in the case of suspicious changes, controller should be able to terminate the whole calibration process.

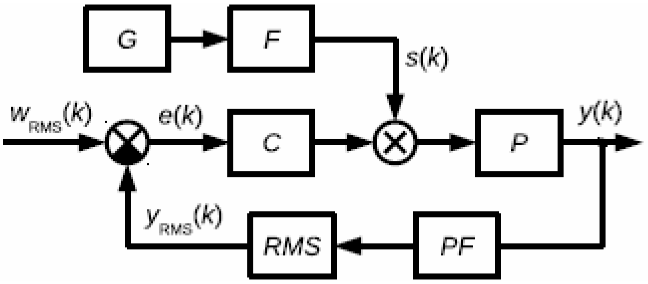


Fig. 3.9: System control scheme [6]

3.3.3 Compensation of total harmonic distortion

The total harmonic distortion, which rises predominantly with higher displacement amplitude can be compensated by following algorithm. The algorithm is based on correct data from the Fourier transform of the signal. Once we know the main components of the signal, we can start generating the fundamental signal and its second harmonic. In each cycle we shift the phase of the second harmonic by 30 degrees and store the actual value of THD. Once we have data after all shifts, we can try to increase the precision by checking the surrounding of the second harmonic again with 5 degree step. When the THD value reaches its minimum, we know, that the second harmonic is in opposite phase against the second harmonic of the vibration exciter. Once we reach the point, the algorithm tries to increase the amplitude of the second harmonic, in order to topple the THD even more. When all cycles of the second harmonic are finished, algorithm moves on the compensation of third harmonics. The process with these cycles is controlled by software relay. It receives settings from the user about the threshold. As soon the harmonic distortion reaches desired value, the stored values are reset and state machine starts regulation and measurement of the current amplitude-frequency.

3.3.4 Calculation of sensitivity and phase shift

Sensitivity is measured according to following formula:

$$S_{qaDUT} = S_{qaREF} \times \frac{v_{REF}}{v_{DUT}} \times \frac{U_{2DUT}}{U_{2REF}} \tag{3.1}$$

$$\tag{3.2}$$

Where
v_{REF} - gain factor of the reference amplifier
v_{DUT} - gain factor of the DUT amplifier
U_{2DUT} - output voltage of the device under test
U_{2REF} - output voltage of the reference sensor
S_{qaDUT} - sensitivity of reference transducer
S_{qaREF} - sensitivity of device under test

Phase shift is calculated as follows:

$$P_{DUT} = P_{DUT-REF} + P_{REF} - P_{ampDUT} \tag{3.3}$$

$$\tag{3.4}$$

Where
P_{DUT} - phase shift of device under test
$P_{DUT-REF}$ - measured phase shift between device under test and reference transducer

P_{REF} - phase shift of the reference transducer
P_{ampDUT} - phase shift of the signal conditioner connected to DUT

Extended measurement uncertainties are obtained by multiplying the standard measurement uncertainties by extension factor k = 2. The values of the measuring quantity fall into the assigned intervals with a probability of 95%.

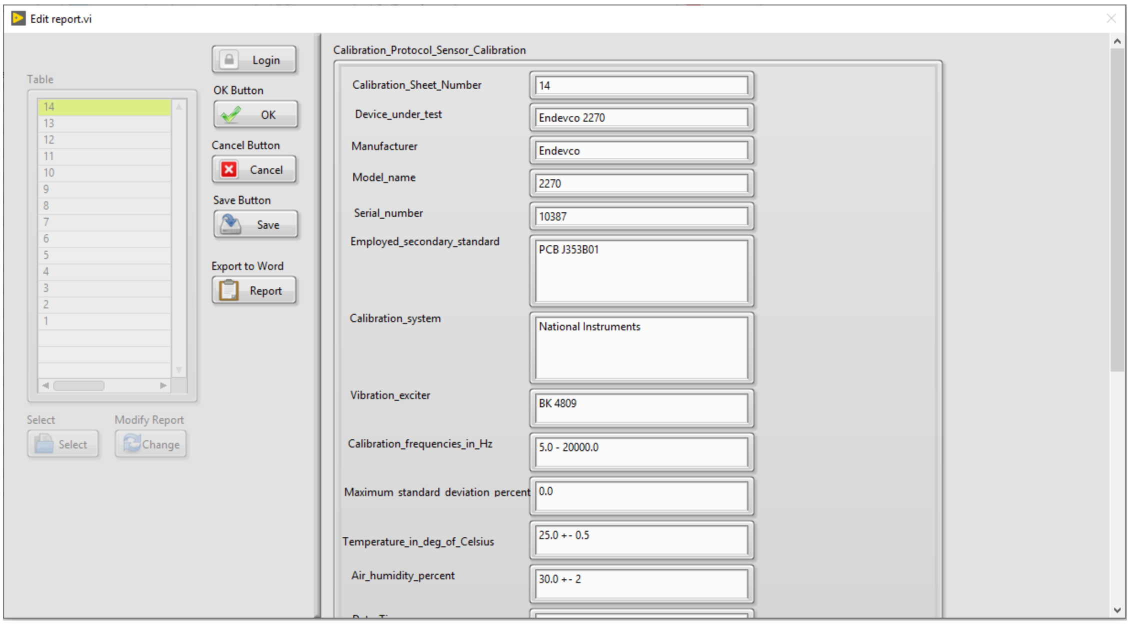
3.3.5 Transfer of data between PC and NI-DAQ chassis

The measured data can be immediately seen on the front panel in the sub-panel block. User is able to see signal from both sensors in time domain, frequency analysis of both sensors and table with values for each frequency as it is prepared for the calibration certificate. The time domain data wont be stored in the memory. Only data which will be passed for the sake of calibration certificate will be stored in memory.

3.4 Processing of calibration results

3.4.1 Report generation

When calibration run is finished, calibration report is automatically generated. User can add further details to the report and save it. As most of the important data are filled in automatically, user has to add only few information about the temperature and relative humidity to the report.



Calibration_Protocol_Sensor_Calibration

Calibration_Sheet_Number	14
Device_under_test	Endevco 2270
Manufacturer	Endevco
Model_name	2270
Serial_number	10387
Employed_secondary_standard	PCB J353B01
Calibration_system	National Instruments
Vibration_exciter	BK 4809
Calibration_frequencies_in_Hz	5.0 - 20000.0
Maximum standard deviation percent	0.0
Temperature_in_deg_of_Celsius	25.0 +- 0.5
Air_humidity_percent	30.0 +- 2

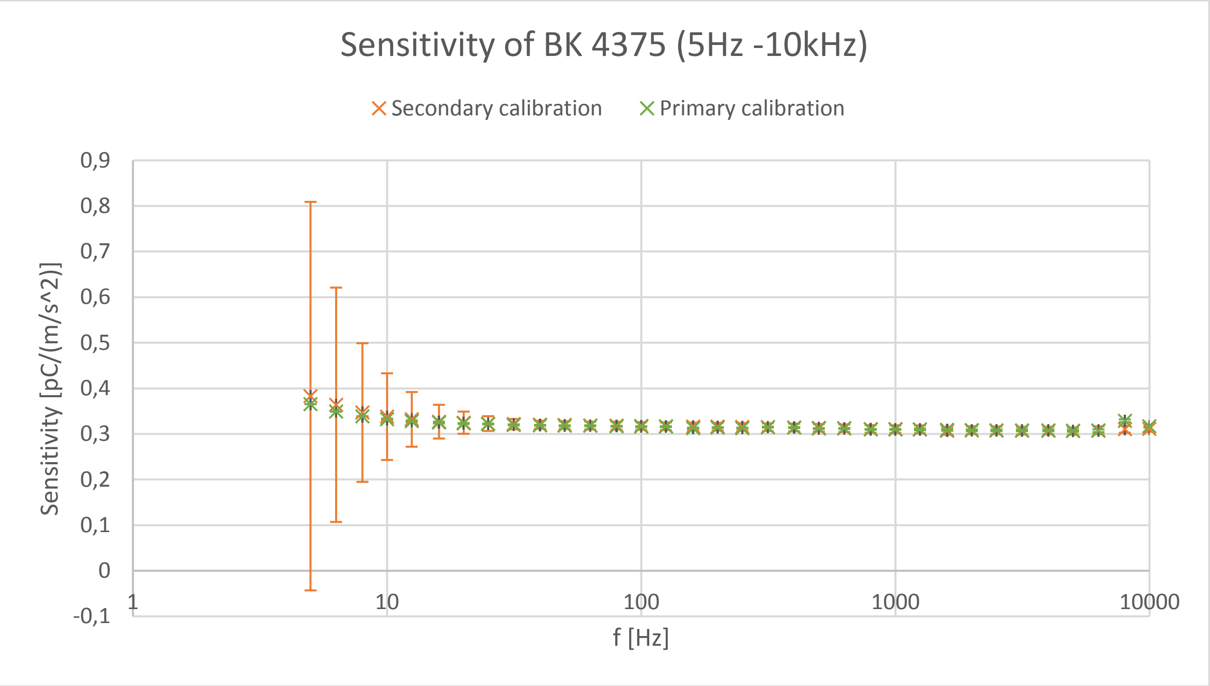
Fig. 3.10: Report database

3.4.2 Calibration certificate

Calibration certificate can be prepared automatically from the data of the calibration report. The layout of the calibration certificate can be seen in the Suffix of the thesis. After hitting button Calibration Report, dialog window opens so that we can specify, which template should be used for final presentation of the measured data. The word template is automatically filled with new data and can be stored or printed.

4 Verification of the functionality

The system was verified on the level of user interface for diverse scenarios of creating a Test description. The measurement system was tested for number of different combinations of acceleration and frequency levels. To test the precision of the calibration equipment and method, we can use reference standard PCB J353B01 for calibration of another reference standard BK 4375, which will for the sake of the experiment serve as the device under test. As BK 4375 is used also as reference sensor, we have available data of primary calibration. The results of the secondary calibration of the BK 4375 can be compared with the results of primary calibration of the same sensor and thus we can obtain absolute and relative error of the calibration as well as EN score. The following results where obtained by calibration of accelerometer BK 4375 with reference standard PCB J353B01. In order to utilize some range of the input card, and minimize the uncertainty, we used acceleration of 50 m/s^2. As we restricted the maximum displacement to 1.5mm Peak - Peak, desired acceleration is reached only at frequency 50Hz. The uncertainty in the lower frequencies is therefore much greater, because the range of input card is used poorly. At frequencies higher than 40 Hz, we obtain uncertainty of approximately 2.7 %. Compared to the relative error, which is mostly less than 1%, we can say, that the uncertainty is calculated very strictly. This outcome is also evident from the EN score, for most of the frequencies below 0.5. There are two exceptions, where the results of the primary calibration and the secondary calibration do not match. At low frequencies of 5 - 8 Hz the error may be caused by the 0.1Hz high-pass filter of the charge amplifier M68D1 and 0.43Hz high-pass filter of the input card, which may have caused some attenuation at that frequencies. Furthermore the harmonic distortion at 5Hz is still 4.6% and 6.3Hz 3% after compensation. However the measurement is compatible, as the uncertainty of secondary calibration at low frequencies was extremely high. The second exception is the incompatible result at the frequency 8kHz where we obtained EN score 2.3. According to primary calibration, the sensor BK 4375 has small resonance at that frequency and deviates from the reference value measured at 80Hz by 3.89%. This resonance was not measured during secondary calibration what can be caused by several reasons. The most plausible one is that the calibration setting of secondary calibration is different compared to the primary. The reference sensor was mounted to the DUT from the top with use of mounting pad with weight around 40 grams. Together with the primary sensor could the weight on the top of the device under test reach 60 grams. This weight most probably altered the transfer function the amplitude-frequency response of the sensor and shifted the resonance frequency out of the measured scope. According to attainable uncertainties of the complex sensitivity stated in ISO 16063-21, we fulfill the requirements for uncertainty only for the range between 2kHz - 10 kHz. In order to obtain desired uncertainty also with lower frequencies, two options can be considered. First possibility would be to use reference sensor and signal conditioners with such sensitivity, that voltage on both channels of the input card would reach at least 10% of the input range of the measurement card. At lower frequencies displacement of the vibration exciter should be utilized in the most effective and safe manner. The second possibility would be to recalculate the weight of uncertainties in the budget, if all typical conditions can be met. However this second option can have only minor effect on the uncertainty compared to the first one. Measurement of phase shift is not mandatory for secondary calibration. In the showcase measurement, the absolute error of secondary calibration compared to primary is up to 3%. This is mainly caused by absence of precise calibrated data for the exact setting of the charge amplifier M68D1, which was set to use down-pass filter with cut-off frequency 50kHz. Measurement is therefore inaccurate and we use increased uncertainty to illustrate that. The total harmonic distortion can be compensated to reach levels required in ISO 16063-21. The difference between calibration with and without compensation of THD can be seen in the appendix, where we include calibration certificates of acceleration sensor Endevco 2270 with and without compensation of THD. Other parameters of generation equipment are within required ranges, as can be seen in Chapter 2. The following table and graphs illustrate the precision of the secondary calibration compared to the primary calibration.



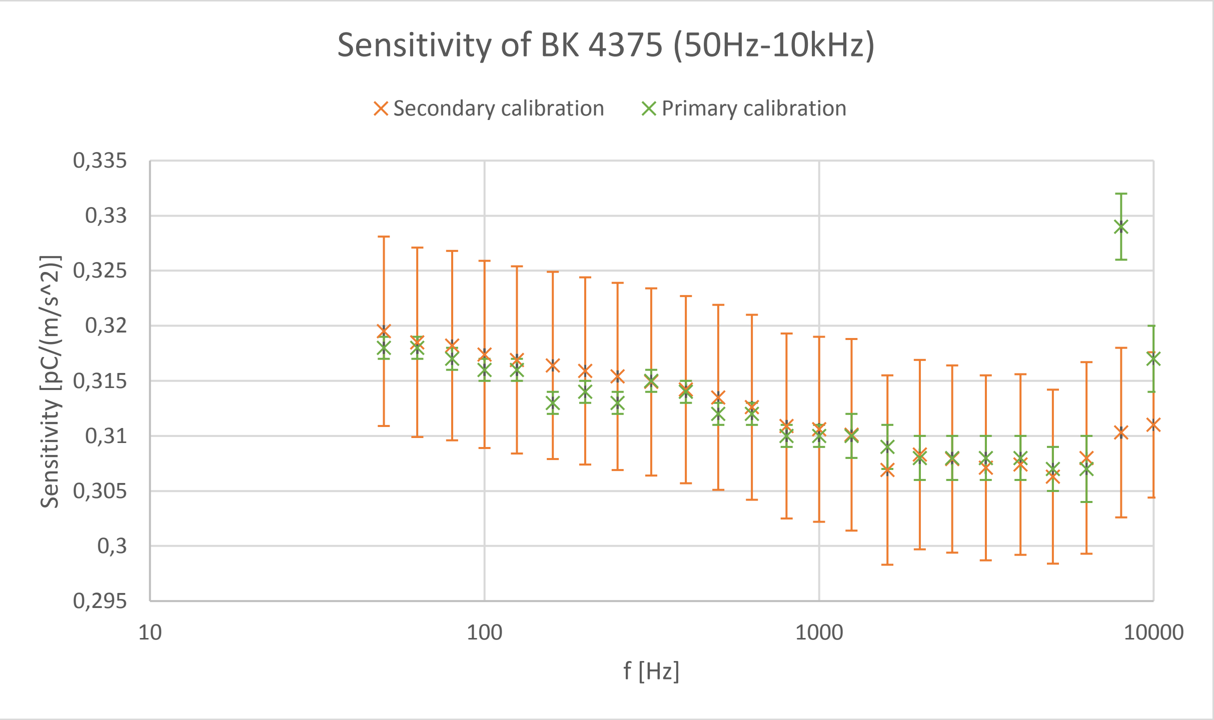


Fig. 4.1: Sensitivity BK 4375

Frequency[Hz]	Acceleration [m/s^2]	Sensitivity [pC/(m/s^2)]	Uncertainty [pC/(m/s^2)]	Uncertainty [%]	DUT sensitivity by primary calibration [pC/(m/s^2)]	Uncertainty [pC/(m/s^2)]	EN score [-]	Relative error [%]
5	0.72	0.4	0.5	125	0.36549	0	0.1	8.6
6.3	1.17	0.4	0.3	75	0.34934	0	0.2	12.7
8	1.89	0.3	0.2	66.7	0.33859	0	0.2	-12.9
10	2.95	0.34	0.09	26.5	0.332	0.002	0.1	2.4
12.5	4.61	0.33	0.06	18.1	0.328	0.002	0.1	1.2
16	7.57	0.33	0.04	11.3	0.325	0.002	0.1	0.6
20	11.80	0.32	0.02	7.5	0.323	0.001	0.1	0.6
25	18.47	0.323	0.016	5.0	0.322	0.001	0.0	0.2
31.5	29.38	0.322	0.011	3.5	0.32	0.001	0.1	0.5
40	47.36	0.320	0.009	2.7	0.319	0.001	0.1	0.4
50	49.99	0.320	0.009	2.7	0.318	0.001	0.2	0.5
63	49.99	0.319	0.009	2.7	0.318	0.001	0.1	0.2
80	49.99	0.318	0.009	2.7	0.317	0.001	0.1	0.4
100	49.99	0.317	0.009	2.7	0.316	0.001	0.2	0.4
125	49.99	0.317	0.009	2.7	0.316	0.001	0.1	0.3
160	49.99	0.316	0.009	2.7	0.313	0.001	0.4	1.1
200	49.99	0.316	0.009	2.7	0.314	0.001	0.2	0.6
250	49.99	0.315	0.009	2.7	0.313	0.001	0.3	0.8
315	49.99	0.315	0.009	2.7	0.315	0.001	0.0	0.0
400	49.99	0.314	0.009	2.7	0.314	0.001	0.0	0.1
500	49.98	0.314	0.008	2.7	0.312	0.001	0.2	0.5
630	49.99	0.313	0.008	2.7	0.312	0.001	0.1	0.2
800	49.98	0.311	0.008	2.7	0.31	0.001	0.1	0.3
1000	49.98	0.311	0.008	2.7	0.31	0.001	0.1	0.2
1250	49.98	0.310	0.009	2.8	0.31	0.002	0.0	0.0
1600	49.98	0.307	0.009	2.8	0.309	0.002	0.2	-0.7
2000	49.99	0.308	0.009	2.8	0.308	0.002	0.0	0.1
2500	49.98	0.308	0.009	2.8	0.308	0.002	0.0	0.0
3150	49.98	0.307	0.008	2.7	0.308	0.002	0.1	-0.3
4000	49.98	0.307	0.008	2.7	0.308	0.002	0.1	-0.2
5000	49.98	0.306	0.008	2.6	0.307	0.002	0.1	-0.2
6300	49.99	0.308	0.009	2.8	0.307	0.003	0.1	0.3
8000	49.99	0.310	0.008	2.5	0.329	0.003	2.3	-6.0
10000	49.99	0.311	0.007	2.1	0.317	0.003	0.8	-1.9

Tab. 4.1: Calibration result of BK 4375 Sensitivity

Frequency[Hz]	Acceleration [m/s^2]	Phase DUT [°] DUT[°]	Uncertainty [°]	THD DUT [%] -	Phase primary calib [°]	Uncertainty [°]	EN Score [-]	Absolute error [°]
5	0.72	180	4	4.060	179.9	0	0.1	-0.3
6.3	1.17	179	4	1.910	179.7	0	0.2	-0.7
8	1.89	179	4	1.770	179.5	0	0.2	-0.9
10	2.95	178	4	1.709	179.4	1	0.3	-1.2
12.5	4.61	178	4	2.908	179.4	1	0.3	-1.4
16	7.57	178	4	1.430	179.4	1	0.4	-1.7
20	11.80	178	4	1.175	179.3	1	0.4	-1.7
25	18.47	177	4	1.820	179.3	1	0.4	-1.8
31.5	29.38	177	4	1.550	179.3	1	0.5	-2.0
40	47.36	177	4	0.740	179.3	1	0.5	-2.1
50	49.99	177	4	0.340	179.3	1	0.5	-2.1
63	49.99	177	4	0.150	179.4	1	0.5	-2.3
80	49.99	177	4	0.130	179.4	0.5	0.6	-2.3
100	49.99	177	4	0.100	179.3	1	0.5	-2.2
125	49.99	177	4	0.070	179.3	1	0.5	-2.3
160	49.99	177	4	0.080	179.2	1	0.5	-2.2
200	49.99	177	4	0.070	179.4	1	0.6	-2.4
250	49.99	177	4	0.070	179.4	1	0.6	-2.4
315	49.99	177	4	0.070	179.4	1	0.6	-2.4
400	49.99	177	4	0.090	179.1	1	0.5	-2.1
500	49.98	177	4	0.080	179.2	1	0.5	-2.3
630	49.99	177	4	0.122	179.1	1	0.5	-2.2
800	49.98	177	4	0.169	179.2	1	0.5	-2.3
1000	49.98	177	4	0.207	179.2	1	0.5	-2.3
1250	49.98	177	4	0.406	179.2	1	0.5	-2.3
1600	49.98	175	4	0.498	179.2	1	1.1	-4.7
2000	49.99	177	4	0.980	179.2	1	0.5	-2.3
2500	49.98	177	4	0.573	179.2	1	0.5	-2.3
3150	49.98	177	4	0.593	179.1	1	0.5	-2.2
4000	49.98	177	4	1.315	179.1	1	0.5	-2.2
5000	49.98	177	4	1.386	179.1	1	0.6	-2.4
6300	49.99	177	5	0.772	180.1	2	0.7	-3.4
8000	49.99	177	5	0.181	179.2	2	0.5	-2.4
10000	49.99	177	5	2.503	178.1	2	0.3	-1.3

Tab. 4.2: Calibration result of BK 4375 Phase

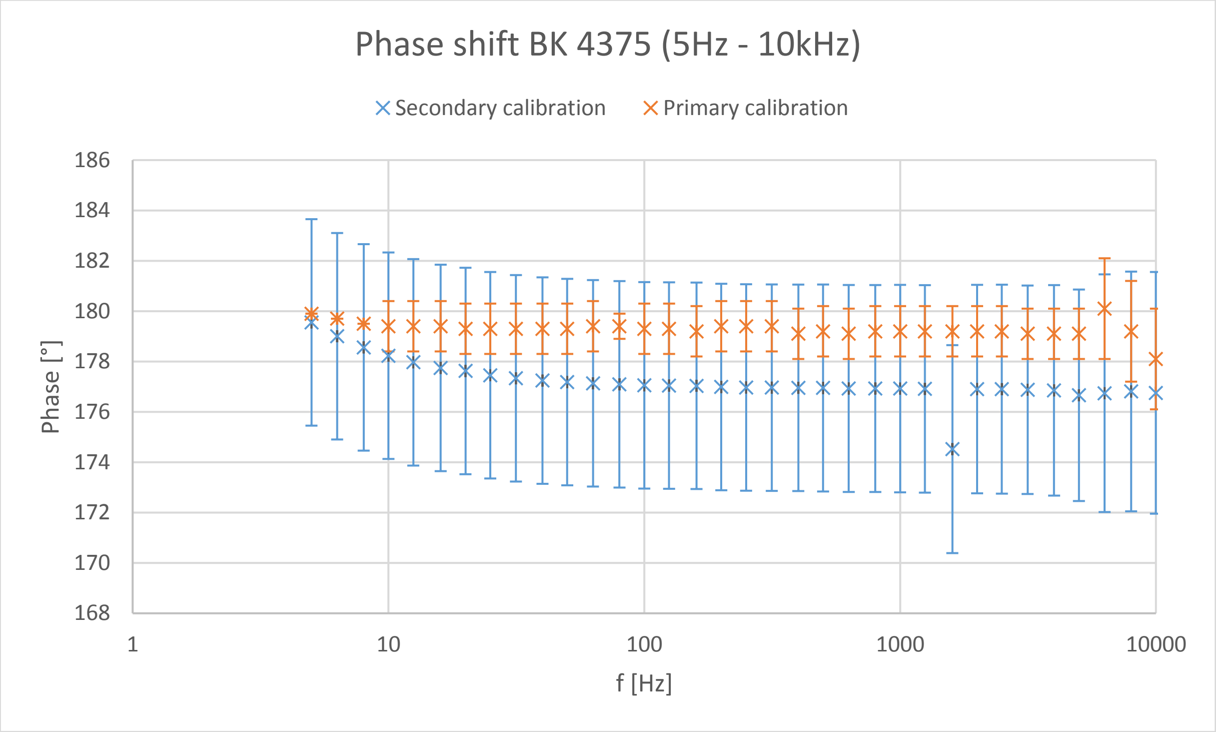


Fig. 4.2: Phase shift BK 4375

5 Conclusion

Based on the technical requirements and current practices in vibration measurement, the bachelor thesis describes the design of the compact measurement system used for secondary calibration of vibration sensors. From the software point of view, we have achieved to define and design the basic structure of the calibration program which can be used for secondary calibration of vibration sensors. The program consists of three distinct parts: Definition of the test description, Control program and Generation of the calibration certificate. The main structure utilizes the structure of Queued message handler and Control program is based on state machine architecture. The functionality of the program was tested on two different vibration exciters using several reference sensors and devices under test, signal conditioners and charge amplifiers. The tested range extends from 5Hz to 10kHz. Calibration on frequencies higher than 10 kHz was not part of the test. Maximum testing acceleration used was $50m/s^2$. Requirements of ISO 16063-21 were fulfilled within the range from 2 kHz to 10 kHz. If the input voltage range of the measurement card is utilized by about 10% and higher, the system should be able to fulfill requirements of the ISO 16063-21 in its whole frequency range when used with suitable reference transducers and amplifiers calibrated in accordance with suitable primary methods. The outcome and evaluation of the calibration can be seen in the chapter 4 Verification of the functionality. The examples of calibration reports are enclosed in appendices.

Bibliography

[1] BUEHN, U. *Compendium of vibration calibration.* Spektra Schwingungstechnik und Akustik GmbH, Dresden. 2007.

[2] DEIERLEIN, Dr. BUEHN, SCHMIDT, WESEGNIK. *Documentation Software CS18,* Version 2.13, SPEKTRA Schwingungstechnik und Akustik GmbH, Dresden. 2013.

[3] BITTER, Rick, Taqi MOHIUDDIN, Matt NAWROCKI. *LabView advanced programming techniques.* 2nd ed. Boca Raton, FL: CRC Press, c2007. ISBN 978-0849333255.

[4] CALA, Martin. *ÍDICÍ SYSTÉM PRO ELEKTRODYNAMICKÝ BUDI VIBRACÍ.* Brno, 2014. Diplomová práce. Vysoké uení technické v Brn. Vedoucí práce Ing. Zdenk Havránek, Ph.D.

[5] CALA, Martin. Control system for a small electrodynamic exciter. In: *Proceedings of the 2015 16th International Carpathian Control Conference* (ICCC). Szilvásvárad: IEEE, 2015, s. 64-68. DOI: 10.1109/CarpathianCC.2015.7145047. ISBN 978-1-4799-7370-5. ISSN -. Dostupné také z: <`http://ieeexplore.ieee.org/document/7145047/`>.

[6] CALA, Martin. Few Issues Related to an Electrodynamic Exciter Control. In: *Proceedings of the 21st Conference STUDENT EEICT 2015.* Brno: -, 2015, s. 450-454. ISBN 978-80-214-5148-3. ISSN -.

[7] ISO 16063-21:2003. *Methods for the calibration of vibration and shock transducers: Part 21: Vibration calibration by comparison to a reference transducer.* Geneva: ISO copyright office, 2003.

[8] Firemní literatura National Instruments [online]. [cit. 2019-01-01]. Dostupné z: <`www.ni.com`>.

[9] Firemní literatura Brüel & Kjær [online]. [cit. 2019-01-01]. Dostupné z: <`www.bksv.com`>.

[10] GABAY, Jon. Fundamentals of Piezoelectric Shock and Vibration Sensors. *Digi-Key Electronics* [online]. -: -, 2011 [cit. 2019-01-01]. Dostupné z: <`https://www.digikey.com/en/articles/techzone/2011/dec/fundamentals-of-piezoelectric-shock-and-vibration-sensors`>.

List of symbols, physical constants and abbreviations

$a(t)$	acceleration
C	capacity
DUT	Device under test
f_s	sampling rate
GUI	Graphical user interface
ICP	Integrated Electronics Piezo-Electric
IEPE	Integrated Electronics Piezo-Electric
LabVIEW	Laboratory Virtual Instrument Engineering Workbench
NI	National Instruments
NI DAQmx	National Instruments' current-generation data acquisition driver
RMS	root mean square
S_{qa}	reference sensor sensitivity
S_{qaDUT}	sensitivity of device under test
$s(t)$	displacement
THD	Total harmonic distortion
U	electrical voltage
$u(t)$	alternating electrical voltage
UI	User interface
$v(t)$	velocity
v	gain factor of the amplifier
VI	Virtual Instrument

List of appendices

A Calibration certificates `thesis`

A.1 Calibration certificate Endevco

Brno University of Technology
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Technická 3082/12, 616 00 Brno
Tel: +420 5 4114 6411, Fax: +420 5 4114 6451
E-mail: uamt@feec.uamt.vutbr.cz, http://www.feec.vutbr.cz

Calibration Certificate No. 13

Date: 17/05/2019

Object

Name:	Endevco 2270
Manufacturer:	Endevco
Type:	2270
Serial number.:	10387

Customer:

Environmental Conditions

Temperature [°C]:	25.0 +- 0.5	
Relative humidity [%]:	30.0 +- 2	
Frequency range [Hz]:	5.0 - 10000.0	
Vibration direction:	**LF:** --	**HF:** Vertical

Results

Sensitivity :	0.206 +- 0.006pC/(m/s^2)
Ref.frequency [Hz]:	80
Acceleration [m/s^2 Peak]:	49.989333

Results are documented in table no. 1, graph 1 and graph 2

Statement

This calibration certificate may not be reproduced other than in full and is valid for the above-specified calibrated sensor under documented test conditions and methods of calibration. Calibration certificate without signature is not valid.

Approval

Date of calibration	Stamp	Approved by	Calibrated by
17.5.2019			Peter Siket

Brno University of Technology
Faculty of Electrical Engineering and Communication
The Department of Control and Instrumentation
Technická 3082/12, 616 00 Brno
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Calibration Method

Calibration was performed by using the method of secondary calibration according to the Directive ISO 16063-21. The transducer was exposed to sinusoidal acceleration which was applied by means of an electrodynamic vibration exciter. The acceleration was measured with the reference transducer, which is integral part of the moving element.

Measurement Uncertainty

The specified values are the extended measurement uncertainties obtained by multiplying the standard measurement uncertainties by extension factor k = 2. They were ascertained in line with EA-4/02. The values of the measuring quantity fall into the assigned intervals with a probability of 95 %.

Components of the Reference Measuring Equipment:

Calibration system:	National Instruments
Vibration Exciter:	BK 4809
Reference standard transducer LF:	-
Reference standard transducer HF:	PCB J353B01

Comments

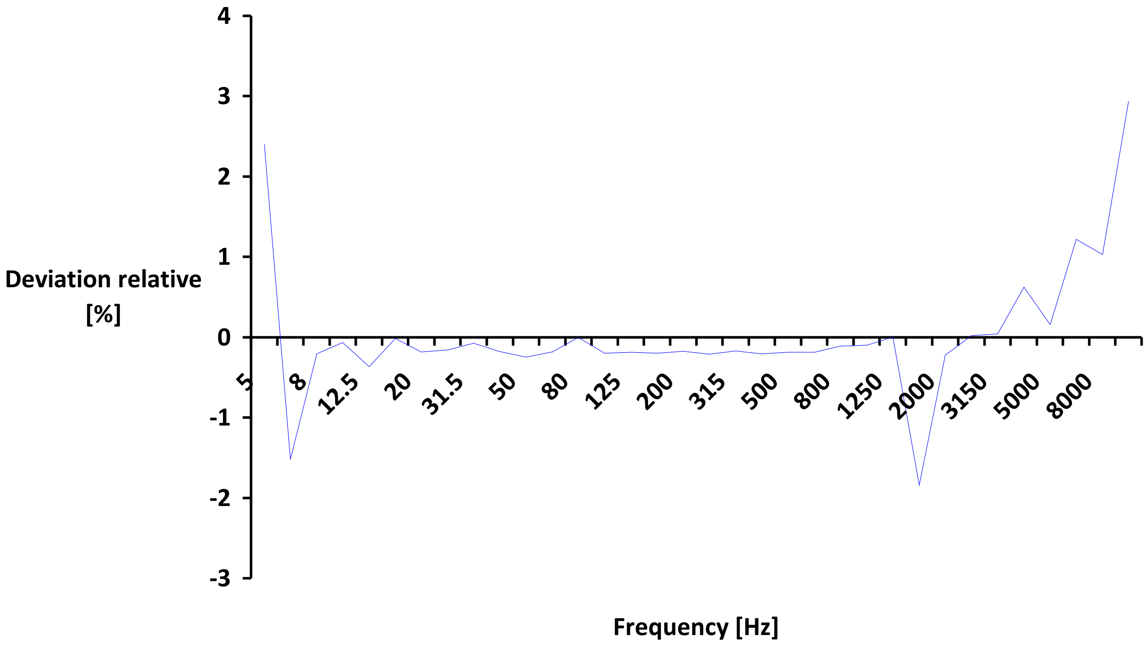
Without THD compensation

Tab. 1 Frequency response

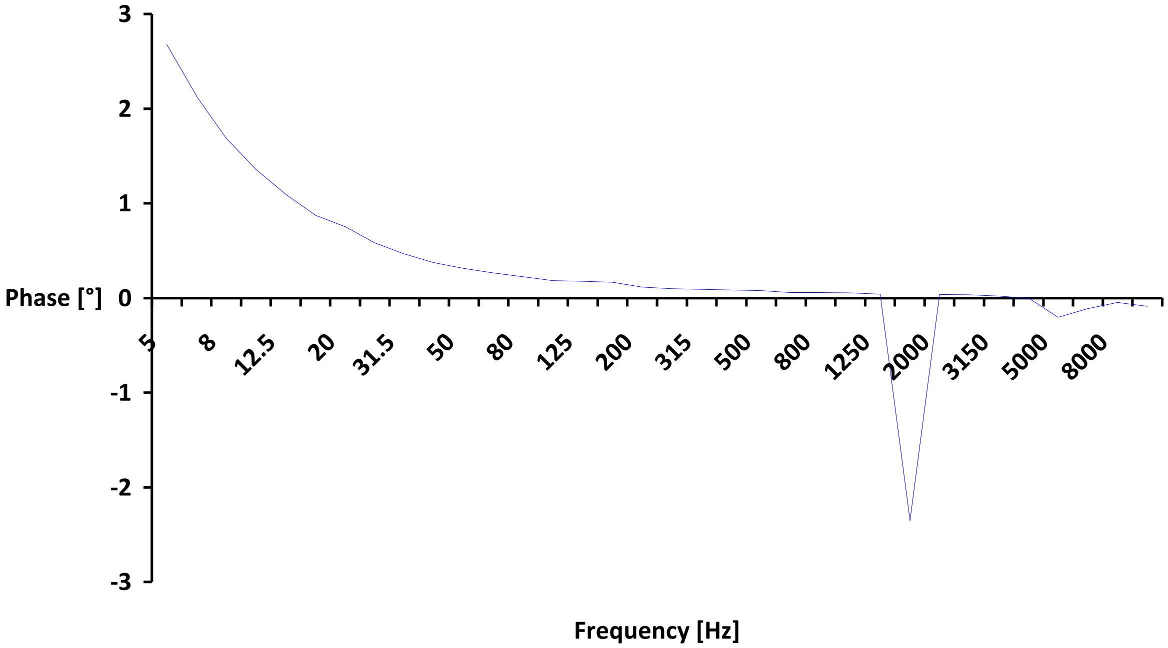
Frequency [Hz]	Acceleration [m/s^2]	Transfer coefficitent [pC/(m/s^2)]	Uncertainty [pC/(m/s^2)]	Deviation from reference frequency [%]	Phase shift [°]	Uncertainty [°]	Total harmonic distortion reference [%]	Total harmonic distortion [%]
5.0000	0.7230	0.2110	0.2915	2.4031	2.6785	0.5001	12.1409	12.0773
6.3000	1.1730	0.2029	0.1743	-1.5172	2.1300	0.5001	13.7355	13.7515
8.0000	1.8915	0.2056	0.1094	-0.2034	1.6891	0.5002	15.2351	15.2682
10.0000	2.9531	0.2059	0.0701	-0.0648	1.3591	0.5002	18.1381	18.0588
12.5000	4.6143	0.2053	0.0449	-0.3635	1.0965	0.5003	16.0407	16.0662
16.0000	7.5654	0.2060	0.0277	-0.0119	0.8756	0.5003	9.3581	9.3339
20.0000	11.8005	0.2057	0.0181	-0.1803	0.7560	0.5004	5.6219	5.6172
25.0000	18.4674	0.2057	0.0120	-0.1564	0.5847	0.5005	2.8185	2.8185
31.5000	29.3750	0.2059	0.0082	-0.0738	0.4644	0.5006	1.5878	1.6020
40.0000	47.3630	0.2057	0.0061	-0.1749	0.3744	0.5008	0.7272	0.7149
50.0000	49.9930	0.2056	0.0060	-0.2439	0.3146	0.5010	0.3707	0.3569
63.0000	49.9917	0.2057	0.0060	-0.1809	0.2643	0.5013	0.1593	0.1619
80.0000	49.9893	0.2061	0.0060	0.0000	0.2237	0.5016	0.1297	0.1425
100.0000	49.9932	0.2057	0.0060	-0.1987	0.1853	0.5020	0.1027	0.1125
125.0000	49.9936	0.2057	0.0060	-0.1865	0.1764	0.5025	0.0696	0.0687
160.0000	49.9902	0.2057	0.0060	-0.1951	0.1670	0.5032	0.0721	0.0767
200.0000	49.9925	0.2057	0.0060	-0.1734	0.1183	0.5040	0.0633	0.0639
250.0000	49.9937	0.2056	0.0060	-0.2080	0.1000	0.5051	0.0665	0.0675
315.0000	49.9915	0.2057	0.0060	-0.1675	0.0921	0.5064	0.0704	0.0768
400.0000	49.9895	0.2056	0.0060	-0.2065	0.0850	0.5081	0.0839	0.0850
500.0000	49.9815	0.2057	0.0060	-0.1857	0.0785	0.5101	0.0852	0.0889
630.0000	49.9854	0.2057	0.0060	-0.1842	0.0605	0.5127	0.1157	0.1186
800.0000	49.9836	0.2058	0.0060	-0.1091	0.0580	0.5162	0.4375	0.4093
1000.0000	49.9792	0.2059	0.0060	-0.0974	0.0550	0.5202	0.6690	0.5996
1250.0000	49.9797	0.2061	0.0062	0.0016	0.0436	0.5253	1.3675	1.2450
1600.0000	49.9844	0.2023	0.0061	-1.8406	-2.3490	0.5323	2.1982	1.8550
2000.0000	49.9850	0.2056	0.0062	-0.2196	0.0383	0.5404	3.4644	3.1598
2500.0000	49.9802	0.2061	0.0062	0.0208	0.0364	0.5505	1.9690	1.7444
3150.0000	49.9806	0.2062	0.0062	0.0443	0.0204	0.5637	2.2966	2.0373

4000.0000	**49.9836**	**0.2074**	**0.0062**	**0.6274**	**-0.0031**	**0.5808**	**6.2658**	**5.2212**
5000.0000	**49.9833**	**0.2064**	**0.0062**	**0.1598**	**-0.2017**	**0.6010**	**6.1387**	**5.6512**
6300.0000	**49.9886**	**0.2086**	**0.0072**	**1.2193**	**-0.1109**	**1.1273**	**5.9023**	**4.9581**
8000.0000	**49.9919**	**0.2082**	**0.0071**	**1.0331**	**-0.0443**	**1.1617**	**0.8623**	**0.7975**
10000.0000	**49.9941**	**0.2121**	**0.0072**	**2.9412**	**-0.0857**	**1.2021**	**10.9635**	**8.7705**

Graph 1 Amplitude-Frequency Response



Graph 2 Phase-Frequency Response



A.2 Calibration certificate Endevco with THD compensation

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Calibration Certificate No. 14

Date: 17/05/2019

Object

Name:	Endevco 2270
Manufacturer:	Endevco
Type:	2270
Serial number.:	10387

Customer:

Environmental Conditions

Temperature [°C]:	25.0 +- 0.5	
Relative humidity [%]:	30.0 +- 2	
Frequency range [Hz]:	5.0 - 40.0	
Vibration direction:	**LF:** --	**HF:** Vertical

Results

Sensitivity :	0.206 +- 0.006pC/(m/s^2)
Ref.frequency [Hz]:	80
Acceleration [m/s^2 Peak]:	49.991870

Results are documented in table no. 1, graph 1 and graph 2

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17.5.2019			Peter Siket

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Reference standard transducer LF:	-
Reference standard transducer HF:	PCB J353B01

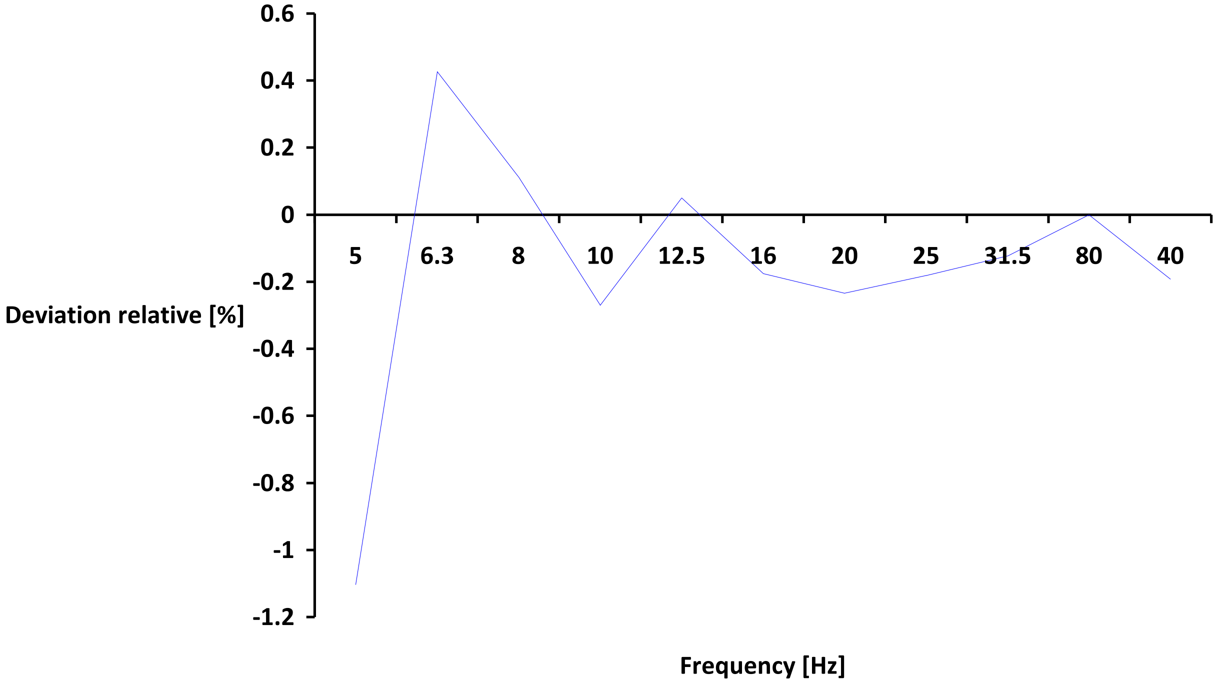
Comments

THD Compensation

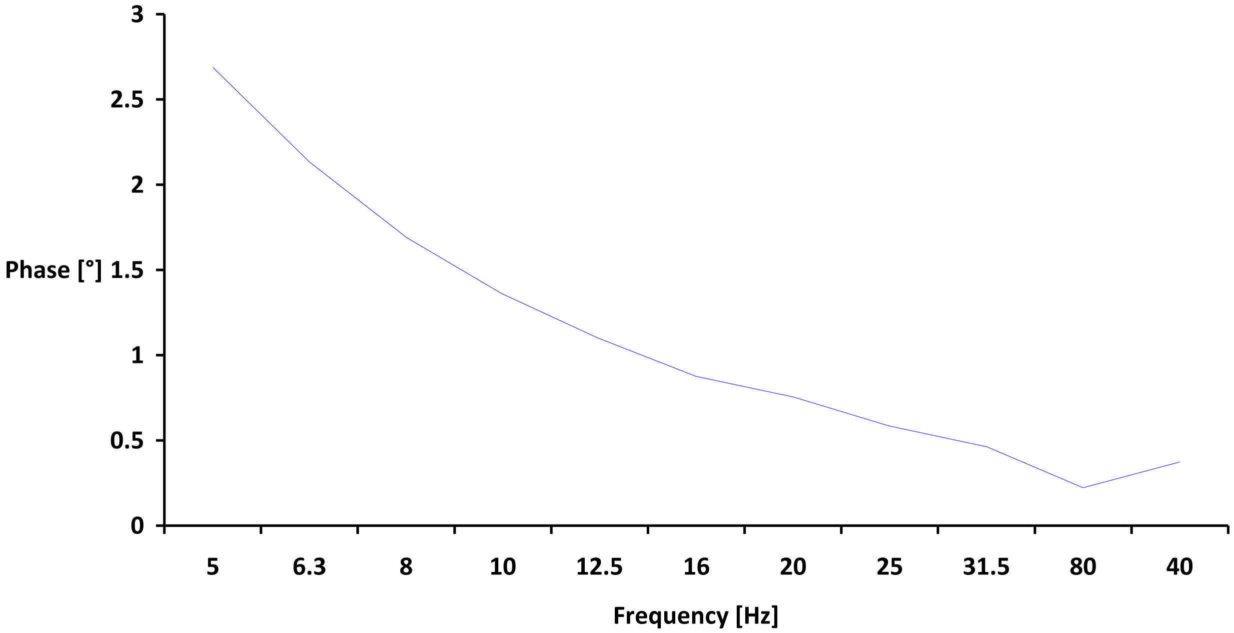
Tab. 1 Frequency response

Frequency [Hz]	**Acceleration [m/s^2]**	**Transfer coefficitent [pC/(m/s^2)]**	**Uncertainty [pC/(m/s^2)]**	**Deviation from reference frequency [%]**	**Phase shift [°]**	**Uncertainty [°]**	**Total harmonic distortion reference [%]**	**Total harmonic distortion [%]**
5.0000	**0.7260**	**0.2039**	**0.2840**	**-1.1026**	**2.6877**	**0.5001**	**4.4883**	**4.6098**
6.3000	**1.1750**	**0.2070**	**0.1768**	**0.4269**	**2.1339**	**0.5001**	**3.0409**	**2.9705**
8.0000	**1.8873**	**0.2064**	**0.1095**	**0.1138**	**1.6914**	**0.5002**	**1.7955**	**1.6892**
10.0000	**2.9559**	**0.2056**	**0.0699**	**-0.2696**	**1.3584**	**0.5002**	**1.8057**	**1.7665**
12.5000	**4.6115**	**0.2062**	**0.0450**	**0.0504**	**1.0977**	**0.5003**	**2.4784**	**2.4795**
16.0000	**7.5724**	**0.2058**	**0.0276**	**-0.1755**	**0.8762**	**0.5003**	**1.4480**	**1.4573**
20.0000	**11.8285**	**0.2057**	**0.0180**	**-0.2340**	**0.7560**	**0.5004**	**1.1750**	**1.1942**
25.0000	**18.5305**	**0.2058**	**0.0119**	**-0.1808**	**0.5846**	**0.5005**	**1.8204**	**1.8180**
31.5000	**29.3790**	**0.2059**	**0.0082**	**-0.1224**	**0.4643**	**0.5006**	**1.5840**	**1.5969**
80.0000	**49.9919**	**0.2061**	**0.0060**	**0.0000**	**0.2241**	**0.5016**	**0.1169**	**0.1321**
40.0000	**47.3610**	**0.2057**	**0.0061**	**-0.1920**	**0.3745**	**0.5008**	**0.7380**	**0.7149**

Graph 1 Amplitude-Frequency Response



Graph 2 Phase-Frequency Response



B Content of the attached CD

On the attached CD is stored the version of the calibration program valid at the time of thesis submission. The program was developed on LabVIEW 2017 on 64-but Windows 10. The version of the LabVIEW Run-Time Engine that matches the major release of the Development Environment used to create the executable will be needed. The version should be intended for the Operating System on which will be running the executable (Windows, Mac or Linux).