ACTA IMEKO
ISSN: 2221-870X
September 2026, Volume 15, Number 3, 1 - 7

Enhancing accelerometer calibration results by reporting interpolated calibration data

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ABSTRACT
This paper describes the implementation of interpolation methods (fitting curves) for reporting complex (magnitude and phase) accelerometer calibration measurements. The authors' evaluation focused on two interpolation methods: polynomial fit and mathematical model description of a charge accelerometer. Charge accelerometers, such as the Brüel & Kjær model 8305 and the ENDEVCO model 2270, are the de facto laboratory standard accelerometers. NMIs have been maintaining sensitivity calibration data, with the associated uncertainty of measurement (UoM), on such devices for decades and reported publicly available comparison data using these accelerometers, which provide ample vetted data for curve-fitting technique investigations.

Section: RESEARCH PAPER

Keywords: calibration; accelerometer; mathematical model; interpolate; polynomial; regression

Citation: I. Veldman, A. Maina, H. Volkers, Enhancing accelerometer calibration results by reporting interpolated calibration data, Acta IMEKO, vol. 15 (2026) no. 3, pp. 1-7. DOI: 10.21014/actaimeko.v15i3.1917

Section Editor: Francesco Lamonaca, University of Calabria, Italy

Received July 24, 2024; **In final form** March 9, 2026; **Published** September 2026

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1. INTRODUCTION

Metrologists globally have been tasked with the calibration of accelerometers for decades. The need for calibration is driven by the same requirement for all metrological parameters, ensuring measurements performed globally are traceable to the SI and internationally comparable. Through the implementation of the CIPM MRA [1], Consultative Committees (organs of the BIPM) and other international organizations, such as the International Organization for Standardization (ISO), the goal to meet industry's vibration measurement requirements has been met to an acceptable degree. Technological advancement drives improved product development, requiring improvements in measurement accuracy, speed, methods, and more. Mindful of this, the international vibration metrology community continuously initiates projects to improve existing vibration measurement standards and to develop new ones.

One such recent standard is ISO 16063-43, Methods for the calibration of vibration and shock transducers — Part 43: Calibration of accelerometers by model-based parameter identification [2]. The implementation of this standard initiated further investigation into the reporting of interpolated vibration calibration results with the propagation of uncertainties of the model parameters.

The application of interpolated data with regard to vibration calibration has been reported on by a number of authors, not only in terms of calibration [3], but also in terms of vibration measurement capability comparison [4], [5], and comparison reference value analysis [6].

Furthermore, regression of accelerometer calibration data, independent of the method applied, provides the functionality to determine sensitivity values through interpolation at frequencies of interest that might not have been calibrated. This advantage is extending into the use of an accelerometer as part of a measurement system or instrument, where only the parameters to calculate the sensitivity over a defined frequency range of interest with unrestricted frequency resolution are required. Another aspect of importance and value is the reduced Uncertainty of Measurement (UoM), under qualifying circumstances and Expanded Uncertainty of the Model (EMU).

In Section 2, the authors provide some detail regarding data interpolation methods, focusing on single-degree-of-freedom (1DoF), two-degrees-of-freedom (2DoF) model-based and polynomial fit (PolyFit) methods. Also, in Section 2, the authors discuss software methods implemented to realize data interpolation results and the EMU.

In Section 3, the authors provide the results obtained and a comparison of the results using the different methods. The authors review the results presented and draw some conclusions in Section 4.

2. DATA INTERPOLATION IMPLEMENTATION

Metrologists often perform the calibration of an artifact over a range, resulting in a data set with an associated UoM. When performing secondary and/or primary accelerometer calibration as prescribed in [7] to [10], one typically produces around 40 sensitivity calibration data points, spanning the frequency range from 10 Hz to 10 kHz, and around 60 points for calibrations performed up to 20 kHz. These empirically obtained data points (discrete values) represent the values of a function for a limited number of values of the independent variable. With regression, one derives a simple function from the given discrete data set, such that the function line passes closest to all the discrete data points. By applying the function, using interpolation, one can determine data points in between the provided data points. In mathematics, several interpolation methods are generally implemented: linear, polynomial and spline interpolation. The focus of this paper is model-based and polynomial interpolation. Two models were considered for the model-based interpolation: a single-degree-of-freedom model (1DoF) and a two-degrees-of-freedom model (2DoF). For this work, the authors used interpolation as they did not extend the results beyond the empirical data frequency range, even though the model parameters could easily be used for data extrapolation.

A word of caution: regression should be used with proper understanding of the underlying data. The formulated function cannot discern whether the data is correct or not. Be aware of the presence of systematic errors. For instance, a DC offset in the dataset will be present in the resulting model data.

2.1. Why ISO 16063-43?

Reference [2], the standard ISO 16063-43, Methods for the calibration of vibration and shock transducers — Part 43: Calibration of accelerometers by model-based parameter identification, was developed as a complement to existing methods (procedures) and a bridge between the existing vibration signal classes, stationary signals, and transient signals. The limitations with regard to the different methods and classes are well described in the Introduction of [2].

Throughout the history and development of vibration metrology, discrepancies have been observed between calibration results obtained by different National Metrology Institutes (NMIs), and, in time, discrepancies in calibration results considering stationary signals and transient signals [5]. These differences exceeded the UoM associated with the measurements and were thus not metrologically equivalent. Investigations revealed that there exists good correlation between the calibration results, within the linear portion of the transducer frequency response. These investigations were needed for establishing transducer shock sensitivity calibration procedures using transient signals [8] and [10]. Unfortunately, at present, the generation of mechanical shocks does not facilitate full control of the transient signal being generated with respect to the signal shape and time duration (pulse width). When using the transducer in its non-linear frequency region (as the sensor moves towards its resonance peak), knowledge of the frequency content of the transient signal is paramount.

The implementation of [2] results in the estimation of parameters describing a 1DoF mathematical model (simple linear mass-spring-damper model), describing the input–output characteristic of vibration transducers. The model parameters are estimated based on the discrete data sets obtained using standard calibration procedures according to ISO 16063-21 [7], ISO 16063-22 [8], ISO 16063-11 [9], and ISO 16063-13 [10]. With the model defined by the estimated parameters, the transducer sensitivity can be calculated more accurately, be it for stationary or transient signal applications.

2.2. Model-based interpolation (1DoF)

The National Metrology Institute of South Africa (NMISA) developed a software application to implement ISO 16063-43 [2] using Delphi™. The software program closely follows the flow chart for the estimation of the model parameters depicted in Figure 3 in [2]. Delphi allows the user to implement powerful matrix mathematic algorithms to solve the model parameters. When determining the model parameters (S_0, f_n, and ζ), NMISA aimed to report model-based calibration results (interpolation results), rather than the model parameters themselves. As a result, the calculation of the EMU associated with the model parameters, as described in [2], was not given priority and was not implemented (developed as part of the Delphi application) at the time of this publication.

The discrete data is read in from an MS Excel© file, which serves as a database file, used by NMISA as a result sheet for reporting primary accelerometer calibration results. By solving (1), the model parameters S_0, f_n, and ζ are estimated. In (1), $\hat{S}(f)$ is the accelerometer sensitivity function based on a 1DoF model, S_0 is the accelerometer low frequency sensitivity value (typically at $f \leq 160$ Hz), f is the frequency of interest, f_n is the accelerometer resonance frequency, and ζ is the damping factor.

With the model parameters estimated, the accelerometer frequency response, based on the model parameters, is calculated and plotted by the software application, on the same graph as the experimentally measured discrete values frequency response.

$$\hat{S}(f) = \frac{S_0}{\sqrt{\left[1 - \left(\frac{f}{f_\mathrm{n}}\right)^2\right]^2 + 4\,\zeta^2\,\left(\frac{f}{f_\mathrm{n}}\right)^2}}\,. \tag{1}$$

Using the already estimated model parameters, the accelerometer phase response, $\Delta\hat{\varphi}(f)$, is calculated as per (2) and plotted together with the experimentally measured discrete value phase response.

$$\Delta\hat{\varphi}(f) = -\arctan\left[\frac{2\,\zeta\left(\frac{f}{f_n}\right)}{1 - \left(\frac{f}{f_n}\right)^2}\right]. \tag{2}$$

Figure 1 shows a graph of the frequency response of the complex sensitivity (magnitude and phase) of a Brüel & Kjær 8305s BtoB charge output accelerometer. The measured results are plotted with markers, while the synthesized FRF based on the fitted model function is represented by a curve without markers.

2.3. Method validation

A crucial aspect of implementing a new procedure is the validity thereof, as required by ISO -17025 [11]. At the time when NMISA was developing the software application to implement [2], the Kenya Bureau of Standards (KEBS) established parameter identification capabilities [3] as per [2].

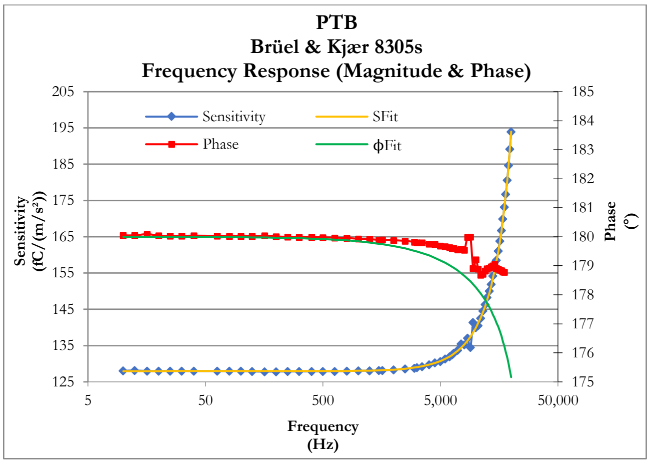

Figure 1. Brüel & Kjær 8305s accelerometer calibration data: Measured and model-based results.

KEBS implemented the Levenberg-Marquardt method to solve the non-linear least squares problem. This was successfully done using Octave™.

NMISA and KEBS exchanged and compared experimental data, effectively verifying the applications implemented by the two NMIs. The peer reviewed, published accelerometer calibration data of the recent CIPM key comparison, CCAUV.V-K5 [12], was used to verify the validity and robustness of the two applications. This dataset [12] provided discrete data for model fitting of single-ended (SE) as well as double-ended (BtoB) accelerometers.

A subset of the model parameters determined by NMISA and KEBS are reported in Table 1 and Table 2, respectively. The complex sensitivity frequency response was synthetized for all participants in CCAUV.V-K5, using the model parameters as determined by NMISA and KEBS.

Frequency responses, using the calculated 1DoF model parameters reported in Table 1 and Table 2, were synthetized for all participants in [12], for both the SE and BtoB, accelerometers. For illustration purposes, the sensitivity results synthetized for the SE accelerometer, based on the PTB data set, is shown in Figure 2, with the phase results shown in Figure 3.

During the validation process, substantial differences between the reported measured phase data and the calculated model-based phase responses were noted. It was determined that the NMISA software application determines resonant frequency

Table 1. SE accelerometer model parameters using a subset of CCAUV.V-K5 participants data, estimated by NMISA.

NMI	S_0 (fC/(m/s²))	f_n (Hz)	ζ
PTB	126.51	31 594	0.0395
DPLA	126.52	32 237	0.0569
NIST	126.60	31 258	0.0439
INMETRO	126.71	31 847	0.0375
NMISA	126.66	31 943	0.0426
NMIA	126.76	31 168	0.0493

Table 2. SE accelerometer model parameters using a subset of CCAUV.V-K5 participants data, estimated by KEBS.

NMI	S_0 (fC/(m/s²))	f_n (Hz)	ζ
PTB	126.50	30 967	0.0032
DPLA	127.77	35 233	0.0221
NIST	126.39	30 386	0.0052
INMETRO	126.64	31 122	0.0052
NMISA	126.56	31 256	0.0110
NMIA	129.07	31 599	0.0000

values, f_n, that are too low, and damping factor values, ζ, that are inaccurate. This was not purely due to the application algorithm execution. Recent studies [13] have shown that the 1DoF model is not optimal, and that a 2DoF model more closely models the behaviour of piezo-electric transducers, specifically charge accelerometers.

2.4. Polynomial-based interpolation

Broadly speaking, the aim of data fitting is to define the parameters of a mathematical function that would represent a dataset as closely as possible. This measure of "as close as possible" is generally defined by the sum of the squares of the residuals or weighted least squares, chi-square, χ^2.

Polynomial regression (General Least Squares) is to fit a set of data to a model of M specified functions of x with the general form being:

$$(x) = \sum_{k=1}^{M} a^k X_k(x)\,, \tag{3}$$

where $X_1(x),\ldots, X_M(x)$ are the basis functions.

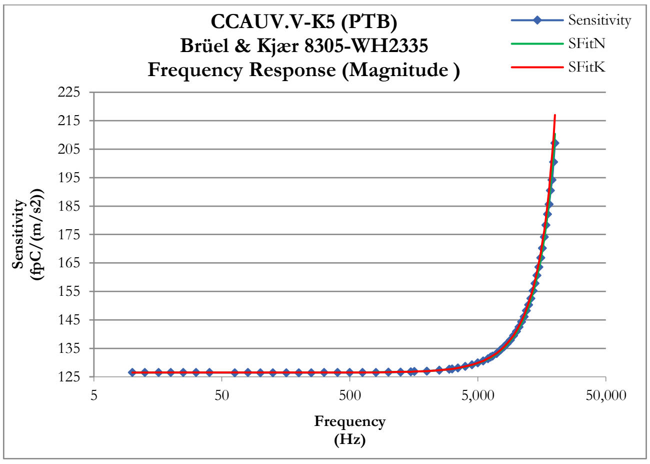

Figure 2. Brüel & Kjær 8305s accelerometer sensitivity calibration data: CCAUV.V-K5, NMISA 1DoF, and KEBS 1DoF model-based results.

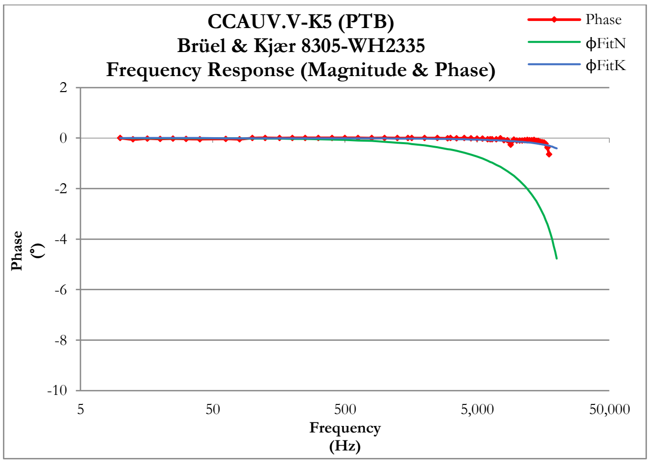

Figure 3. Brüel & Kjær 8305s accelerometer phase calibration data: CCAUV.V-K5, NMISA 1DoF, and KEBS 1DoF model-based results.

One selects parameters to minimise χ^2 using the merit function in equation (4). Here, σ_i is the standard deviation of the i^{th} data point:

$$\chi^2 = \left[\sum_{i=1}^{N} \frac{y_i - \sum_{k=1}^{M} a_k\, X_k(x_i)}{\sigma_i}\right]^2 . \tag{4}$$

Many fitting techniques are available and commonly used, easy to implement, and execute fast, using the power of modern personal computers (PCs). NMISA implemented equation (4) using Delphi™.

When performing General Least Squares fitting to data [14], the value of χ^2 can be used as a measure of the goodness of the fit. For uncertainties that are uncorrelated $\chi^2 \approx$ degrees of freedom suggests that the equation models the data satisfactorily. The degrees of freedom (d.o.f) is equal to the number of data points minus the number of fitted parameters.

Calculating residuals is a measure of the correlation between synthesized data obtained with interpolation and the data set being modelled. The residuals are the difference between the calibration data that was used as the input to the regression analysis, and the resulting synthesized values obtained by interpolation.

Figure 4 shows a graph of the residuals of the data fitted to PTB SE accelerometer results using a 3rd-order polynomial fit, with the resulting χ^2 = 983 and the d.o.f. = 58.

Figure 5 shows the 4th-order polynomial fitted result using the same data, PTB SE accelerometer. The resulting χ^2 = 36 and the d.o.f. = 57. For the phase response, a 2nd-order fit satisfied the criteria of $\chi^2 \approx$ d.o.f. In Figure 6, the calculated phase response using a 2nd-order polynomial fit together with the PTB data are plotted. For the fit $\chi^2 \approx 2$ and the d.o.f. = 59.

2.5. Model-based interpolation (2DoF)

In the previous sections, it was pointed out that in some instances the 1DoF model does not optimally represent the behaviour of some accelerometers that were modelled.

The accuracy of the model, i.e. how well the model describes the mechanical system, will limit the accuracy of the calibration data produced (synthesized) using the determined model parameters. An understanding of how well the interpolated data represent the data being modelled can be achieved by analysing the residuals.

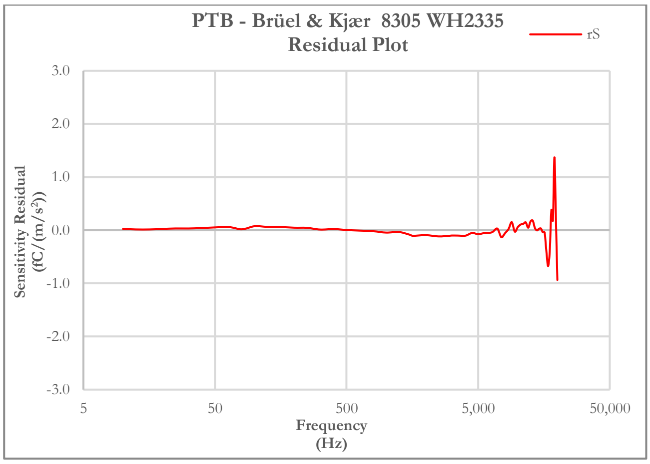

Figure 5. CCAUV.V-K5 calibration data and 4th-order Polynomial fit residual plot of Brüel & Kjær 8305 WH2335 accelerometer.

The accuracy of the model is influenced by the ability to accurately estimate the model parameters, resonant frequency, f_n, and damping factor, ζ.

To improve the model parameters, the resonant frequency of the accelerometer could be determined using measurement procedures reported in [15].

Volkers [13] reported the use of a 2DoF model to describe a mounted accelerometer behaviour in circumstances where a 1DoF model description of the accelerometer is insufficient. Volkers reported a transfer function for the 2DoF model as [13]:

$$\begin{aligned} S_{\text{qa.2DoF}} = {} & [S_0 \cdot \omega_1^2 \\ & \cdot (j\omega\delta_2 + \omega_2^2)]\,\big[\big((\omega_2^2 + \eta\omega_1^2) \\ & + j\omega(\delta_2 + \eta\delta_1) - \omega^2\big)(\omega_1^2 + j\omega\delta_1 - \omega^2) \\ & - \eta(j\omega\delta_1 + \omega_1^2)^2\big]^{-1}, \end{aligned} \tag{5}$$

with

- $\delta_1 = d_1/m_1$, $\omega_1 = \sqrt{c_1/m_1}$ for the damping and the resonance frequency of the seismic system,
- $\delta_2 = d_2/m_2$, $\omega_2 = \sqrt{c_2/m_2}$ for the damping and the resonance frequency of the coupling system,
- $\eta = m_1/m_2$ being the unitless mass relation factor, and
- S_0 being the sensitivity according to [2], [7], or [9].

As reported in [13], Volkers went to great lengths to measure the model parameters. NMISA and PTB shared calibration data

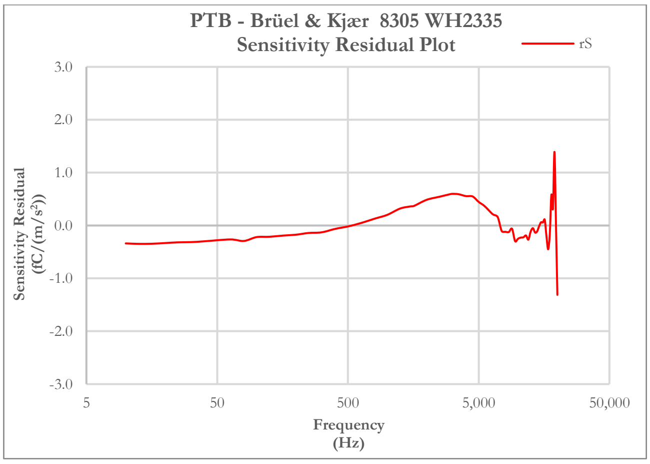

Figure 4. CCAUV.V-K5 calibration data and 3rd-order polynomial fit residual plot of the Brüel & Kjær 8305 WH2335 accelerometer.

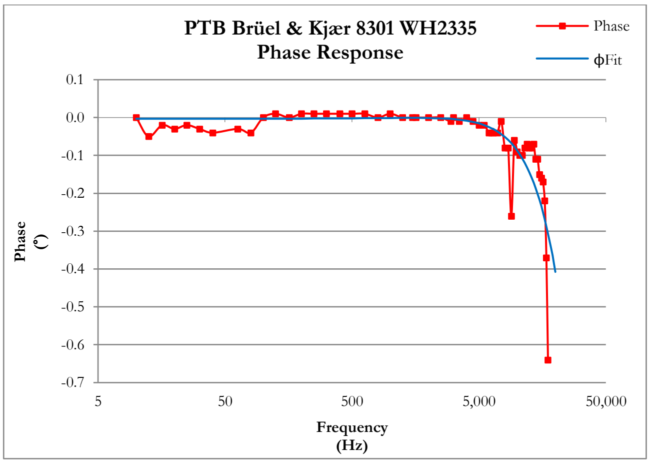

Figure 6. Brüel & Kjær 8305s accelerometer sensitivity calibration data: CCAUV.V-K5, 2nd-order polynomial fit results.

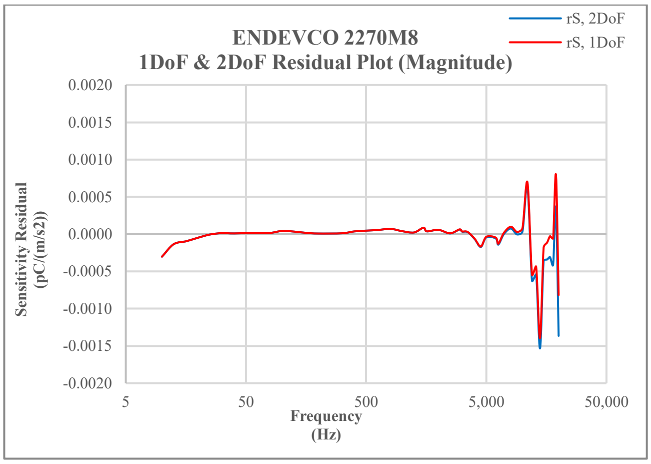

Figure 7. 1Dof and 2DoF sensitivity residual plot for an ENDEVCO 2278M8 SE accelerometer.

for an ENDEVCO model 2270M8 SE accelerometer. Using this data set of 46 complex sensitivity calibration points, covering the frequency range 10 Hz to 20 kHz, 1DoF and 2DoF model parameters were established. The residuals for the sensitivities fitted using both the 1DoF and 2DoF were calculated and are reported in Figure 7. For the fitted models, $\chi^2_{S,1} = 3.7$ and $\chi^2_{S,2} = 4.3$, and the d.o.f. for the 1DoF model was 43, the d.o.f. for the 2DoF model was 40. The residuals for the phase values obtained using both the 1DoF and 2DoF were calculated and are reported in Figure 8. For the model phase results, $\chi^2_{\varphi,1} = 126{,}7$ and $\chi^2_{\varphi,2} = 19.3$, and the d.o.f. for the 1DoF model was 43, the d.o.f. for the 2DoF model was 40.

3. MODEL BASED RESULTS AND UNCERTAINTIES

Although not addressed specifically, the accuracy of fitted results, be it model-based or polynomial-based, is influenced by various parameters. In brief, these influences are the data set UoM, the number of points in the dataset, the accuracy of the model parameter determination (for instance, for a 1DoF model, there is an uncertainty associated with the determination of S_0, f_{n} and ζ), and how well the model describes the electro-mechanical structure. The aim of this report was not to investigate these influences individually, however, through the reporting of results and specific findings, it should become clear which of these parameters need to be considered under which circumstances.

Model-based results are supported by statistical calculations. It is imperative to perform supporting statistical analysis to test the confidence in these results. These include, but should not necessarily be limited to, χ^2 and the d.o.f. When fitting a curve to experimental data by the least squares method, the number of parameters is fixed, depending on the model. In this work, the number of parameters was 3 for the 1DoF model and 6 for the 2DoF model. For polynomial fitting, the order of the fitted polynomial should be kept as low as possible. Here, the guide should be to select a polynomial order that reduces χ^2 to less than or approximately equal to the d.o.f.

The uncertainties associated with the estimated values are obtained by calculating the variance covariance matrix. The minimised value of χ^2 gives an indication of whether the uncertainties of the dataset have been accurately estimated. For this to be valid, the dominant components of uncertainty of the data points should be uncorrelated. In the instance of uncorrelated uncertainty components, the calibration uncertainty at any point (be it for sensitivity or phase) can be found using the covariance matrix produced during the calculation of the coefficients. This uncertainty will usually be smaller than the uncertainties of measurement at the adjacent calibration points by a factor of about:

$$\sigma = \sqrt{\frac{\textit{Number of data points}}{\textit{Number of fitted parameters}}}\,. \tag{6}$$

For this work, an ENDEVCO model 2270M8 SE accelerometer was used to compare all three fitting options of interest. This accelerometer was selected as its behaviour (response) was known and well recorded by PTB and NMISA at the time. Figure 9 serves as a summary plot of all the results recorded. It shows the experimentally measured (calibrated) data, together with the estimated results obtained by the fittings applying the 1DoF model, the 2DoF model, and the 4th-order polynomial model.

The uncertainties for the magnitude and the phase for all three model-based results were calculated. The magnitude residuals are plotted, with the calculated uncertainty, in Figure 10 to Figure 12. Equivalent figures for phase were calculated and plotted. For simplicity, the phase residual plots, with the calculated uncertainties, are not presented here.

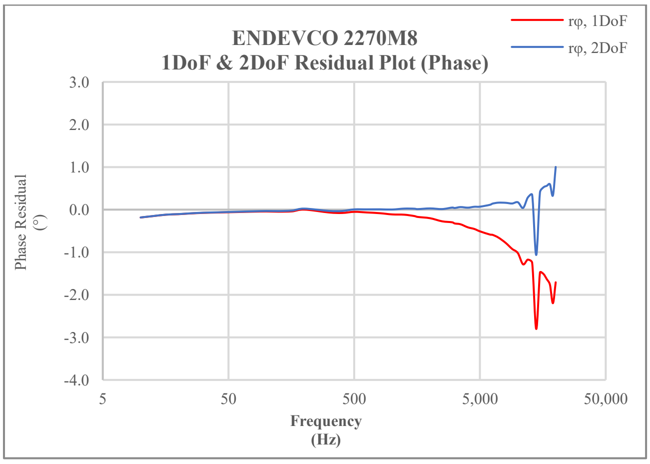

Figure 8. 1Dof and 2DoF phase residual plot for an ENDEVCO 2278M8 SE accelerometer.

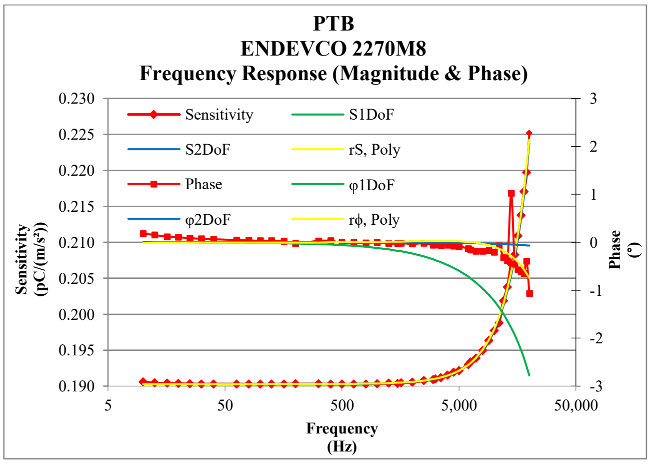

Figure 9. Complex (magnitude & phase) measured, 1Dof, 2DoF and PolyFit results plot for an ENDEVCO model 2278M8 SE accelerometer.

In Figure 10, the residuals of the magnitude of the 1DoF model calculation are shown together with the calculated uncertainty of measurements. The expanded UoM for the dataset (calibrated sensitivities) is plotted on the same graph. This was done to demonstrate the effect that data fitting has on the uncertainty calculation.

In Figure 12, the residuals of the magnitude of the 4th-order PolyFit model calculation are shown together with the calculated uncertainty of measurements.

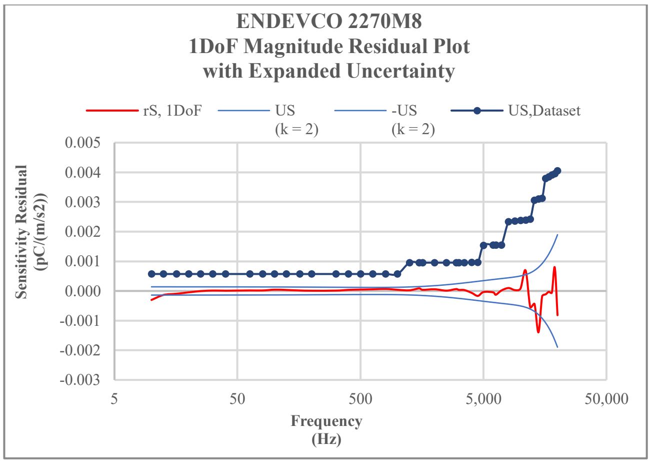

Figure 10. Calculated sensitivity residual values for the 1DoF model, with the calculated uncertainties for an ENDEVCO model 2278M8 SE accelerometer. The uncertainty for the dataset is plotted as well.

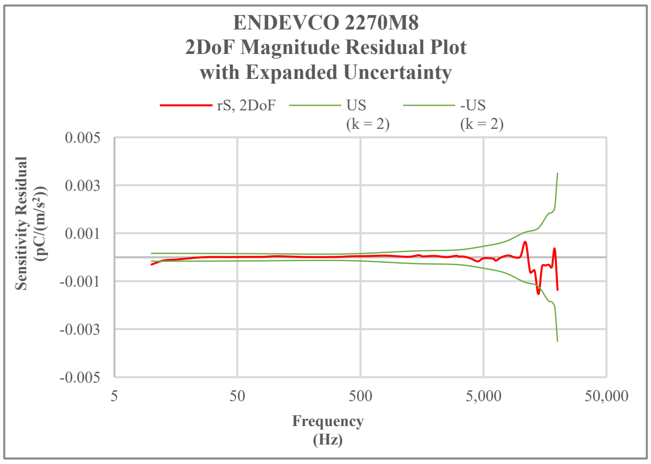

Figure 11. Calculated sensitivity residual values for the 2DoF model, with the calculated uncertainties for an ENDEVCO model 2278M8 SE accelerometer.

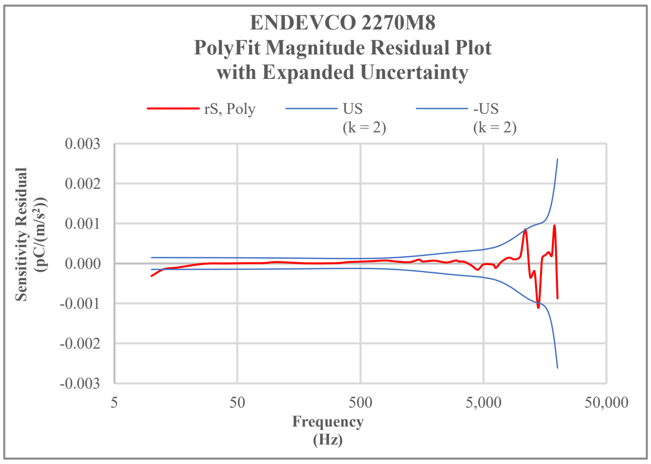

Figure 12. Calculated sensitivity residual values for a 4th-order PolyFit model, with the calculated uncertainties for an ENDEVCO model 2278M8 SE accelerometer.

4. SUMMARY AND CONCLUSIONS

Different techniques for fitting curves to datasets pertaining to vibration calibration have been investigated. It is evident that there is not a single method or model that addresses all unwanted effects recorded during standard accelerometer calibration procedures. The selection of the model to be fitted, either model-based or polynomial-based, should be based on the intended outcome of the calculated results and measurement capabilities available to the metrologist. For instance, is there a procedure in place to determine the accelerometer resonant frequency, or even better, to determine the system resonant frequencies?

The use of polynomial fit techniques allows for the fitting of a curve to the dataset that closely follows the empirical data, that is low χ^2 values. Increasing the number of polynomials needs to be done with care, especially if one is contemplating extrapolating calibration points using high-order polynomials.

Curve fitting is a valuable technique for reporting vibration calibration results. Applying the model/method that bests represent the underlying dataset produces the most reliable data calculations. It supports the calculation of an infinite number of frequency points, and can be implemented easily in measurement systems, as only a few data/parameter points are required.

The use of curve-fitting techniques to report calibration results is complimented by smaller uncertainties.

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