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Application-Oriented Assessment of the Usable Dynamic Bandwidth of Low-Cost MEMS Accelerometers Under Multi-g Sinusoidal Excitation

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***Abstract* – Low-cost MEMS accelerometers are widely employed in embedded sensing, industrial monitoring, automotive electronics, and Industry 4.0 systems because of their low cost, compactness, and ease of integration. However, in dynamic applications, practical deployment requires more than nominal datasheet specifications. The key question is whether the sensor remains fit for purpose over the frequency band of interest under assigned measurement-quality requirements. This work proposes an acceptance-based, application-oriented procedure for determining the usable dynamic bandwidth of low-cost tri-axial MEMS accelerometers under controlled multi-g sinusoidal excitation, by translating experimental dynamic-response evidence into deployment-oriented suitability outcomes. Four nominally identical commercial MEMS units were tested against a reference accelerometer over the 25-800 Hz range and up to 16 g by means of stepped-amplitude harmonic excitation. The measured responses were processed to evaluate compliance with frequency-resolved acceptance criteria based on amplitude tracking quality, uncertainty, and residual dispersion. The procedure aims to identify the frequency interval over which the sensor remains acceptable under explicitly assigned measurement-quality requirements. The results show that the practically acceptable operating range is substantially narrower than what could be inferred from nominal operating specifications alone. The proposed approach provides a practical tool for conformity assessment, sensor selection, and bandwidth-aware deployment of low-cost MEMS accelerometers, while preserving an explicit link between experimental metrological evidence and application-level acceptance requirements.**

Keywords* – *MEMS Accelerometers, Usable Bandwidth, Uncertainty, Dynamic Measurements.

I. INTRODUCTION

Low-cost Micro-Electro-Mechanical Systems (MEMS) accelerometers are increasingly employed in a wide variety of modern sensing applications, including smart sensing platforms, embedded diagnostics, industrial condition monitoring, automotive electronics, wearable devices, and cyber-physical systems [1], [2]. Their broad diffusion is primarily enabled by several well-known advantages, such as miniaturization, low power consumption, ease of integration with digital electronics, and comparatively low manufacturing cost [3]. These characteristics make them particularly attractive whenever large-scale deployment, portability, or embedded implementation is required. However, despite their practical convenience and technological maturity, the effective use of low-cost MEMS accelerometers in dynamic measurement scenarios remains far from trivial.

In fact, nominal datasheet specifications, although useful as a preliminary reference, are often insufficient to support reliable engineering decisions in real operating conditions [4]. Parameters such as measurement range, output data rate, or nominal bandwidth do not fully describe how the sensor behaves when exposed to dynamic excitations over different frequencies and amplitudes, especially under multi-g conditions [5], [6]. In many practical contexts, the issue is not simply whether the sensor provides repeatable signals, but whether its response remains accurate, stable, and sufficiently trustworthy within the frequency interval required by the target application [7]. This distinction is particularly important in fields such as diagnostics, predictive maintenance, structural monitoring, and feedback control, where an apparently functioning sensor may still produce measurements that are no longer adequate for decision-making purposes [8].

From this viewpoint, the problem should not be framed only in terms of characterizing the sensor response through frequency-response trends. Rather, it should be formulated in decisional terms. A sensor is useful in practice only if its measurement performance satisfies explicit acceptance conditions linked to the intended use. Therefore, the central question is not merely how the response evolves with frequency, but up to which frequency the sensor can still be considered acceptable for a given measurement task. This shift from descriptive characterization to decision-oriented assessment is especially relevant for low-cost sensors, whose adoption is often motivated by convenience and scalability, but whose dynamic limitations may become critical when measurement quality must be guaranteed [9].

More specifically, the objective is to identify the highest frequency interval over which the tested sensors preserve a measurement quality compatible with reliable dynamic operation [10].

In this paper, the focus is not on reconstructing a full frequency-dependent calibration framework [11], [12], but on reformulating dynamic experimental evidence into an application-level acceptance outcome. The aim is to determine under which frequency conditions the sensor can still be regarded as suitable for use once explicit quality requirements are assigned.

The contribution of this paper is therefore the reformulation of dynamic experimental evidence into a direct application-level acceptance result. Instead of providing only calibration parameters or response curves, the proposed method yields an interpretable classification of the sensor operating region as acceptable, marginal, or non-acceptable as a function of frequency. This outcome is intended to support deployment decisions by replacing a purely descriptive view of dynamic behavior with an explicit acceptability map linked to the intended measurement task.

II. EXPERIMENTAL SETUP

The experimental investigation was carried out on four nominally identical commercial low-cost MEMS inertial units, hereafter denoted as S1-S4, all based on the LSM6DSO architecture. Each unit integrates a tri-axial accelerometer, which in this study was configured with a full-scale range of ±16 g to ensure compatibility with the maximum excitation levels imposed during the tests. The devices were mounted on a rigid mechanical fixture designed to guarantee stable coupling with the excitation system while minimizing undesired relative motion, misalignment effects, and structural parasitic dynamics. Alongside the MEMS units, a traceably calibrated tri-axial reference accelerometer was co-mounted on the same fixture to provide the reference dynamic acceleration values against which the MEMS responses could be evaluated [13], [14]. The experimental setup is shown in Fig. 1.

Controlled sinusoidal excitation was produced by means of an electrodynamic shaker operating under laboratory conditions. The experimental campaign was designed to explore the sensor behavior over a broad dynamic range, both in frequency and in acceleration amplitude. In particular, the excitation frequency was varied from 25 Hz to 800 Hz, while the applied peak acceleration amplitude followed a stepped profile from 1 g up to 16 g and then back down to 1 g. This ascending-descending sequence was introduced to capture the sensor response over repeated loading conditions and to verify whether the measured behavior remained sufficiently coherent over the full excitation cycle. For each selected test frequency, the shaker generated a sequence of quasi-stationary amplitude plateaus, each corresponding to a prescribed acceleration level maintained for a sufficient time interval to allow stable signal observation.

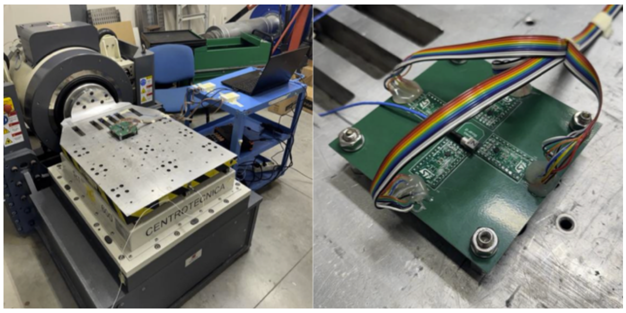

Fig. 1. Experimental setup employed.

For each excitation condition, the steady-state response amplitudes previously extracted from the quasi-stationary plateaus were used as the basis for the present acceptance-oriented assessment. Only the central portion of each plateau was retained to reduce the influence of transition effects and to ensure that the analysis refers to a representative stationary regime. The acceleration amplitude was estimated from the steady-state portion of each plateau after mean removal, using the RMS value converted into peak amplitude under the assumption of sinusoidal excitation [15].

Although the sensors are tri-axial, the present analysis is intentionally restricted to the principal excitation axis. Indeed, from an application-oriented perspective, the principal axis typically represents the most relevant channel for assessing whether the device can be used effectively in dynamic measurement tasks. Focusing on this axis makes it possible to derive a clearer and more stable bandwidth assessment, avoiding possible confounding effects related to cross-axis sensitivity, mounting asymmetries, or secondary mechanical couplings. Accordingly, the results reported in this work are intended to characterize the usable dynamic behavior of the tested low-cost MEMS accelerometers under controlled multi-g excitation in the most practically meaningful sensing direction.

III. ACCEPTANCE-ORIENTED METHODOLOGY

The present assessment starts from frequency-resolved dynamic-response quantities obtained from the experimental dataset and reformulates them into acceptance outcomes. The purpose is not to reproduce the full calibration framework in detail, but to define a compact decision rule through which the practical usability of the sensor can be assessed as a function of frequency.

For each excitation frequency f, the proposed procedure evaluates whether the sensor response satisfies a set of predefined quality requirements directly linked to practical usability. The assessment is based on three frequency-resolved indicators:

- the amplitude tracking error $E_A(f)$, expressing the relative deviation of the MEMS response from the reference-consistent dynamic amplitude transfer;
- the relative uncertainty $u_r(f)$, associated with the extracted steady-state amplitude estimate;
- the normalized residual dispersion $D_r(f)$, expressing the spread of the MEMS amplitude-response points around the local reference-based amplitude-response trend at the same frequency, normalized to the adopted full-scale excitation.

These indicators are used here as decision variables. Their role is not to reconstruct the full sensor calibration law, but to determine whether the sensor remains acceptable under explicitly assigned measurement-quality requirements.

In practical terms, the amplitude tracking error was computed as the relative deviation between the MEMS peak amplitude and the corresponding reference peak amplitude at the same excitation condition.

$$E_{A(f)} = \frac{\left|A_{MEMS}(f) - A_{ref}(f)\right|}{A_{ref}(f)} 100\%, \qquad (1)$$

where $A_{MEMS}(f)$ and $A_{ref}(f)$ denote the estimated peak amplitudes of the MEMS sensor and the reference sensor, respectively, at frequency f.

The relative uncertainty term $u_r(f)$ is associated with the steady-state amplitude estimate extracted from the plateau data. It is defined as

$$u_r(f) = \frac{u_A(f)}{A(f)}, \qquad (2)$$

where $u_A(f)$ is the corresponding standard uncertainty of the estimated peak amplitude $A(f)$. In the present framework, $u_A(f)$ represents the uncertainty contribution associated with the plateau-based amplitude-estimation step and is derived from the variability of the steady-state samples retained for that frequency condition.

At each excitation frequency, the set of amplitude-response points obtained over the imposed acceleration levels was compared with the local reference-based amplitude-response trend. The residuals with respect to this trend were then used to quantify the degree of local scatter of the MEMS response.

The normalized residual dispersion was defined as

$$D_r(f) = \frac{\sigma_{res}(f)}{FS} 100\%, \qquad (3)$$

where $\sigma_{res}(f)$ is the standard deviation of the residuals between the observed MEMS amplitude-response points and the corresponding local reference-based amplitude-response trend at frequency f, while FS is the full-scale value adopted for normalization. Therefore, $D_r(f)$ should not be interpreted as a full calibration parameter, but as a compact indicator of how well the experimental points at a given frequency conform to the local amplitude calibration trend. A low value of $D_r(f)$ indicates that the MEMS response is locally coherent with the reference-based trend, whereas a high value suggests increased scatter, possible nonlinearity, hysteresis, or reduced consistency of the amplitude response. The relative uncertainty and the residual-dispersion indicator therefore capture different aspects of measurement quality. The former refers to the uncertainty associated with the estimated steady-state amplitude itself, whereas the latter describes how consistently the set of amplitude-response points follows the local reference-based trend at the same frequency.

Taken together, these three indicators enable a more complete assessment of dynamic performance. A sensor response may in fact exhibit limited average amplitude error but still present excessive uncertainty or unstable dispersion, which would reduce its practical suitability. Conversely, a low-uncertainty response with excessive tracking deviation would also be inadequate for reliable deployment. For this reason, the procedure adopts a conjunctive acceptance logic: a frequency is considered acceptable only when all selected indicators remain below their prescribed thresholds: $E_A(f) < E_{A,lim}$, $u_r(f) < u_{r,lim}$, $D_r(f) < D_{r,lim}$.

This ensures that the final assessment reflects not just one isolated performance aspect, but the simultaneous satisfaction of multiple quality conditions that are relevant for real measurement use [16], [17].

To account for the fact that different applications impose different levels of stringency, the framework introduces three acceptance levels. The first level, denoted as *Strict*, is intended for high-quality applications in which amplitude reproduction must remain very accurate and the overall measurement quality must satisfy tighter constraints. This level is representative of scenarios in which limited deviations can already compromise the reliability of diagnostics, control, or advanced monitoring tasks. The second level, denoted as *Moderate*, is conceived for general-purpose dynamic measurements, where the sensor is expected to provide reliable behavior without necessarily meeting the most demanding performance targets. The third level, denoted as *Relaxed*, addresses less critical scenarios, in which larger tracking deviations and broader tolerances can still be acceptable, provided that the sensor response remains sufficiently coherent for the intended use.

This multi-level structure makes the procedure more flexible and application aware. Instead of forcing a single universal pass/fail criterion, it allows the same experimental dataset to be interpreted under different operational expectations. As a result, the usable frequency range of the sensor can be expressed in a way that is not only technically meaningful but also directly aligned with the quality requirements of the target task.

The main outcome of the procedure is the usable dynamic bandwidth, defined here as the highest contiguous frequency interval, starting from the lowest tested frequency, over which the sensor continues to comply with the selected acceptance level according to the adopted conjunctive rule. Under this definition, bandwidth is not redefined in the classical transfer-function sense but interpreted as an application-dependent operational limit derived from explicit acceptance criteria. This makes the result particularly suitable for deployment-oriented decision making, since it answers the practical question of up to which frequency the sensor can still be trusted for a given class of applications.

IV. RESULTS AND DISCUSSIONS

A. Acceptance criteria

The adopted acceptance levels are summarized in Table 1. The thresholds reported are not intended as universal or normative limits. Rather, they were selected as application-oriented engineering acceptance thresholds on the basis of three complementary considerations: consistency with the literature on low-cost MEMS accelerometers in vibration-oriented applications; the metrological need to distinguish amplitude fidelity, uncertainty of the estimated amplitude, and local response coherence; and the requirement that the selected values should provide a discriminating but practically meaningful partition of the investigated frequency range. Under this perspective, the strict, moderate, and relaxed levels should be interpreted as three classes of measurement demand rather than as fixed standards.

More specifically, the selected thresholds represent progressively increasing levels of metrological tolerance. The amplitude-tracking limits of 2%, 5%, and 10% were chosen as three progressively relaxed tolerance levels on dynamic amplitude-transfer fidelity, while the uncertainty and residual-dispersion limits were selected to preserve a minimum requirement of metrological reliability and local response coherence across the accepted frequency range.

Table 1. Acceptance criteria for application-oriented bandwidth assessment.

Criterion level	Amplitude tracking error	Relative uncertainty	Normalized residual dispersion
Strict	<2%	<0.8%	<0.3%
Moderate	<5%	<1.0%	<0.5%
Relaxed	<10%	<1.0%	<0.5%

It is worth observing that the thresholds assigned to uncertainty and normalized residual dispersion remain the same for the moderate and relaxed levels, whereas the amplitude-tracking criterion is loosened. This reflects the idea that, even in less stringent applications, the measurement process should remain reasonably stable and not excessively scattered, while some additional amplitude bias may be tolerated depending on the engineering objective. In other words, the framework assumes that reduced accuracy may be acceptable in certain scenarios, but poor repeatability or highly dispersed behavior should still be treated with caution.

The normalized residual-dispersion thresholds correspond to 0.3% and 0.5% of the adopted full-scale excitation, respectively. Overall, the role of Table 1 is to provide a transparent link between metrological indicators and practical decision thresholds, thereby enabling a direct assessment of the usable dynamic range of the tested sensors.

The measured responses were re-elaborated in terms of compliance with the criteria defined in Table 1. When interpreted through this acceptance-based perspective, the results show a clear and physically meaningful trend across the investigated frequency range. At low frequencies, the tested MEMS accelerometers generally satisfy even the strict requirements, indicating that in this region the sensors can reproduce the reference dynamic input with sufficiently limited error, controlled uncertainty, and low residual dispersion. This suggests that, within the lower portion of the investigated band, the dynamic behavior of the devices is compatible with demanding measurement tasks.

As the excitation frequency increases, however, the acceptance margin progressively decreases. The first and most evident limiting factor is the degradation of amplitude tracking quality. In particular, the sensor output becomes increasingly unable to reproduce the input amplitude with the same fidelity observed at lower frequencies. By contrast, the relative uncertainty associated with the steady-state estimates and the normalized residual dispersion remain comparatively better controlled over a wider portion of the frequency range. This indicates that, although the amplitude gain progressively deviates from the reference, the local amplitude-response points remain relatively coherent around their frequency-specific calibration trend over a broader interval. These quantities may also exhibit some deterioration, but they do not emerge as the dominant cause of rejection under the adopted criteria.

This result is important because it clarifies the nature of the practical limitation affecting the tested sensors. The main issue is not the presence of excessive random instability, large point-to-point variability, or uncontrolled noise growth. Rather, the dominant limitation is the progressive loss of amplitude fidelity as the excitation frequency increases. From a metrological viewpoint, this means that the sensors may continue to produce repeatable and apparently stable signals even when the dynamic gain error has become too large for reliable use. From an engineering viewpoint, this is especially relevant because repeatability alone may create a misleading impression of adequate performance if it is not accompanied by sufficient amplitude accuracy.

B. Usable Dynamic Bandwidth

The estimated usable dynamic bandwidth derived from the acceptance procedure is reported in Table 2.

The results clearly indicate that the practical operating range of the tested sensors depends strongly on the required quality level. At the same time, the estimated usable bandwidth is not strictly identical across nominally identical specimens, although the observed inter-sensor dispersion remains limited. Under strict requirements, the usable bandwidth is typically around 175 Hz, with specimen-dependent limits ranging approximately from 100 Hz to 200 Hz. Under moderate requirements, the four tested sensors provide a highly coherent result, with an acceptance limit around 250 Hz. Under relaxed requirements, the usable range extends typically to about 350 Hz, with specimen-dependent limits in the interval from about 325 Hz to 375 Hz.

This result confirms that the effective dynamic limit of the tested MEMS accelerometers should not be interpreted as a single fixed value, but rather as an application-oriented bandwidth interval affected by a limited specimen-to-specimen variability. In practical terms, the moderate threshold provides the most stable reference point across the four tested devices, whereas the strict and relaxed thresholds exhibit a slightly larger but still well-contained dispersion.

A sensor-wise graphical summary of the estimated acceptance limits is reported in Fig. 2. The figure shows that, while the acceptance criteria are common to all devices, the resulting usable bandwidth is only mildly specimen dependent. In particular, the moderate acceptance boundary is highly coherent across the four sensors, whereas the strict and relaxed limits exhibit a limited dispersion range. This representation makes the practical meaning of the acceptance-oriented bandwidth assessment more immediate, especially from a deployment and sensor-selection perspective.

C. Frequency-Band Interpretation

Table 2. Estimated usable dynamic bandwidth of the tested MEMS accelerometers on the principal axis.

Assessment level	Typical usable bandwidth	Observed range across S1-S4
Strict	about 175 Hz	about 100-200 Hz
Moderate	about 250 Hz	about 250 Hz
Relaxed	about 350 Hz	about 325-375 Hz

For practical use, the results can also be summarized by frequency intervals, as reported in Table 3.

This representation is intended as a compact practical summary of the present experimental evidence, rather than as a universal set of fixed boundaries for all devices of the same class.

The lower portion of the investigated band, up to about 100 Hz, can be regarded as safely acceptable under strict criteria for all tested sensors. Between about 100 Hz and 200 Hz, strict acceptance becomes specimen-dependent, reflecting a limited but non-negligible inter-sensor variability. The region up to about 250 Hz remains broadly compatible with moderate acceptance, which appears to be the most coherent criterion across the four tested devices. Beyond this region, the response enters a progressively more application-dependent interval, in which acceptance is generally possible only under relaxed criteria. In particular, the band from about 250 Hz to 325 Hz may still be considered usable in a relaxed sense, while the interval from about 325 Hz to 375 Hz is acceptable only for some specimens. Above about 375 Hz, the tested devices should no longer be considered suitable for accurate amplitude-tracking dynamic measurements.

The resulting outcomes were found to be highly coherent across specimens, although not perfectly identical. In particular, the moderate acceptance boundary was substantially consistent across all four sensors, whereas the strict and relaxed limits exhibited a limited but

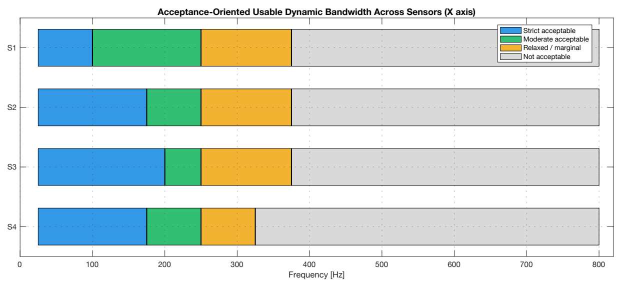

Fig. 2. Acceptance-oriented bandwidth map for sensors S1-S4 on the principal X axis.

Table 3. Frequency-band interpretation of the acceptance outcome on the principal axis.

Frequency band	Assessment outcome
25-100 Hz	Acceptable under strict criteria for all tested sensors
100-200 Hz	Strict acceptance becomes specimen-dependent
200-250 Hz	Generally acceptable under moderate criteria
250-325 Hz	Acceptable under relaxed criteria, depending on the specimen
325-375 Hz	Relaxed acceptance only for some sensors
>375 Hz	Not acceptable for accurate amplitude-tracking use

visible dispersion. This supports the interpretation that the observed behavior is representative of the tested low-cost MEMS family rather than being an isolated characteristic of a single unit.

V. CONCLUSIONS AND OUTLOOK

This work presented an application-oriented procedure for assessing the usable dynamic bandwidth of low-cost MEMS accelerometers under controlled multi-g sinusoidal excitation. Unlike a purely descriptive characterization approach, the proposed framework reformulates the experimental dynamic response into acceptance outcomes based on three complementary indicators: amplitude tracking quality, relative uncertainty, and normalized residual dispersion. In this way, the analysis is shifted from the sole estimation of response parameters to a compliance-oriented assessment of whether the sensor remains fit for purpose as frequency increases.

The results showed that the tested MEMS accelerometers can remain suitable for reliable dynamic measurements only within a frequency interval that is substantially narrower than the nominal bandwidth that might be inferred from manufacturer specifications alone.

A relevant outcome is that the dominant cause of performance loss is not primarily random instability or excessive uncertainty growth, but the progressive degradation of amplitude tracking fidelity as excitation frequency increases. This point is particularly important from an engineering perspective, since it shows that a sensor may still appear stable and repeatable while no longer being sufficiently accurate for reliable amplitude-based dynamic measurements. The acceptance-based interpretation adopted here therefore provides a more realistic view of practical usability than a simple comparison with nominal specifications or a purely descriptive frequency-response analysis.

By translating experimental evidence into direct acceptance outcomes, the framework supports more transparent decisions on whether a low-cost MEMS accelerometer can be confidently employed under given dynamic conditions.

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