Performance Analysis of Commercial Accelerometers of Different Technologies

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***Abstract*—This paper points out the performance and limits of commercial resistive, piezoresistive, piezoelectric, capacitive, thermal and optical accelerometers and can be used as a reference work. Therefore, datasheets of 118 accelerometers from 27 manufacturers of eight countries have been analyzed. Focus of the analysis were the parameters overload shock limit, measurement range, frequency response, resonance frequency, volume, weight, power consumption and operating temperature of both uniaxial and triaxial accelerometers. Accelerometers with overload shock limits in the range of 50 g to 200 x 10^3 g and within a measurement range of 2 g to 110 x 10^3 g have been analyzed. The unit g stands for the gravity acceleration defined as 9.81 meters per square second. A strict overload shock limit of 10 x 10^3 g for accelerometers with proof mass and a measurement range of less than 2 x 10^3 g was found. Also, that the performance of uniaxial and triaxial accelerometers differs. Especially uniaxial piezoelectric accelerometers show a better performance with regard to overload shock, measurement range, resonance frequency, frequency response and operating temperature in contrast to triaxial ones. Piezoelectric accelerometers show the highest overload shock limits, measurement range and operating temperature, capacitive accelerometers the lowest power consumption and volume, piezoresistive accelerometers the widest frequency response.**

Keywords; accelerometers; measurement range; frequency response; resonance frequency; overload shock limit.

I. INTRODUCTION

Within the conducted review, seven transduction principles used in commercial accelerometers today could be identified. The capacitive, piezoresistive and piezoelectric (with charge and with voltage output) principles are most common [1]-[4]. Further principles are the resistive, optical and thermal ones. Reviews of state of the art accelerometers [1][2] are mostly focused on the first three mentioned technologies. This fact and the general lack of reviews of accelerometers as stated in [1], especially comparing different commercial technologies with each other, have been the motivation of the present work. Furthermore, a review including the useful parameters volume, weight, power consumption and operating temperature is missing.

In this paper, we point out the performance of commercial accelerometers by analyzing: a number of 118 accelerometers from 27 manufacturers of eight countries; piezoresistive, resistive, piezoelectric with charge and also with voltage output, capacitive, optical and thermal accelerometers; the parameters overload shock limit, measurement range, frequency response, resonance frequency, volume, weight, power consumption and operating temperature for both uniaxial and triaxial accelerometers. All parameters were stored in a database to identify limits of technologies and correlation between parameters by data mining.

The review includes accelerometers with overload shock limits within the range of 50 g to 200 x 10^3 g and within a measurement range of 2 g to 110 x 10^3 g. The unit g stands for the gravity acceleration defined as 9.81 meters per square seconds. Our review covers commercial accelerometers used in numerous fields, such as consumer, automotive, railway and aerospace industries, with cost per unit within the range of between 1 and 3000 Euro, excluding restricted accelerometers.

In Section 2, the transduction principles of the analyzed accelerometers are explained. The database and the process of data acquisition is addressed in Section 3. In Section 4, the analyzed parameters of accelerometers are discussed and finally, the results are summarized in Section 5.

II. TRANSDUCTION PRINCIPLES OF ACCELEROMETERS

Most accelerometers can be modelled as a spring-mass-damper system. Acceleration applied to the accelerometer leads to a mass displacement or to a bending of a cantilever beam caused by the inertial force. There are a number of transduction principles to detect the displacement of the mass or the bending of the cantilever beam. Common commercial accelerometers detect the change of resistance, capacitance, charge, temperature or optical characteristics caused by mass displacement or bending. Further principles are the resonant, tunneling and electromagnetic principle [2]. But we found no manufacturer selling such accelerometers off-the-shelf.

Each transduction principle needs electronics to convert, e.g., the change in resistance into a voltage signal. Also, for, signal amplifying and processing, electronic circuits are needed. Depending on the transduction principle, either external electronics has to be connected or is combined in one housing. Fundamentally, accelerometers are classified into two types with regard to their frequency response [3]. So called AC accelerometers can only measure dynamic acceleration. The second type that can measure static acceleration, such as gravity acceleration as well as dynamic acceleration is called DC accelerometer.

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A. Piezoelectric accelerometers with charge output

They comprise piezoelectric materials as natural quartz crystals bonded with a proof mass. Acceleration leads to a mass displacement and causes stress in the crystal subsequently. Under stress, the piezoelectric effect causes a charge transfer in the crystal. The amplitude of charge can be measured. Electronics is not integrated so these accelerometers provide a charge signal which has to be transferred by special low noise cable. They work only for AC measurement [3].

B. Piezoelectric accelerometers with voltage output

They work exactly the same way as piezoelectric accelerometers with charge output, but the electronics is integrated to amplify and convert the charge signal into a voltage signal. So they provide a voltage output signal and work only for AC measurement [3].

C. Resistive accelerometers

They detect the change of resistance of a metal strain gauge bonded to a cantilever beam. An acceleration leads to a bending of the cantilever beam and thus to a change in resistance of the strain gauge. For metal foil the geometric effect dominates the piezoelectric effect [5]. Up to four strain gauges are normally configured in a Wheatstone bridge circuit. So they provide a voltage signal and work for DC measurement.

D. Piezoresisitve accelerometers

They work exactly the same way as resistive accelerometers, but the strain gauge is fabricated from semiconductor materials. Single crystal silicon is about 100 times more sensitive to strain because for semiconductors the piezoresistive effect dominates the geometric effect [5]. Configured in a Wheatstone bridge circuit, they provide a voltage signal and work for DC measurement [1].

E. Capacitive accelerometers

They detect changes of capacitance of a plate capacitor. The plates are composed of semiconductor material, such as silicon. The capacitor consists of a moveable plate in-between two stationary plates. The center plate deflects due to acceleration and leads to a change of the capacitance. Configured in a Wheatstone bridge circuit, they provide a voltage signal and work for DC measurement [2][3].

F. Optical accelerometers

Usually, they detect the change of optical characteristics in an optical fiber. There are a variety of technics for fiber optical measurement [6]. The Fiber Bragg Grating (FBG) principle has become widely known [7] and FBG accelerometers seem to be the popular fiber optical technology. Bragg Gratings are interference filters written into optical fibers. The gratings reflect only a narrow spectral component of induced light. This characteristic is used for FBG accelerometers. Acceleration leads to a deformation of an optical fiber attached to a suspension beam. The deformation of the optical fiber changes the reflection characteristic of the Bragg gratings. This change can be detected by comparing the spectral component of the reflected with the induced light. Because usually, electronics is not integrated, they provide an optical signal. They work for DC measurement. In the present work we only analyzed FBG accelerometers.

G. Thermal accelerometers

Thermal accelerometers based on mass displacement have been studied in [8]. We found no manufacturer selling these accelerometers off-the-shelf. Thermal accelerometers without mass displacement have been reported among others in [9]. These types of accelerometers consist of a heater and thermocouples located around the heater in a hermetic chamber. Without acceleration, the heater creates a symmetric temperature profile. When acceleration is applied, the hot air in the chamber moves and the temperature profile gets asymmetric. The asymmetry can be detected by the thermocouples around the heater. There is one manufacturer that patented and commercialized this transduction principle [10]. Electronics is integrated and these accelerometers provide a voltage signal and work for DC measurement. In the present work, we only analyzed thermal accelerometers without moving parts.

III. DATABASE AND PROCEDURE OF DATA ACQUISITION

For this paper, we considered accelerometers worldwide with regard to high overload shock limit, high measurement range, low power consumption and low volume. Table I lists the number of accelerometers classified by their country of origin into European Union and worldwide. We chose the headquarters of manufacture as country of origin because of globalization, engineering, manufacturing, etc., could be distributed across several locations worldwide. For this review, we think the headquarters is the most suitable parameter to compare the performance of accelerometers by countries because from 27 manufactures, 15 manufacture their accelerometers at the headquarters, and 7 manufacture at the headquarters and one or more locations worldwide. Only for 5 manufactures, the location of manufacture is not explicitly specified.

TABLE I. NUMBER OF ANALYZED ACCELEROMETERS CLASSIFIED BY HEADQUARTER OF COMPANY INTO EUROPEAN UNION AND NON EU.

Country of origin	*Number of Accelerometers*	*Classification by country of origin*
Germany	35	European Union (EU)
UK	11	
Denmark	11	
USA	37	Worldwide (Non EU)
Switzerland	13	
China	9	
Canada	1	
Hong Kong	1	

Table I is not exhaustive, but we found no commercial accelerometers with higher overload shock limit, higher measurement range and so on.

Table II shows the number of analyzed accelerometers classified by their transduction principle and classified by frequency response into AC and DC measurement.

TABLE II. NUMBER OF ANALYZED ACCELEROMETERS CLASSIFIED BY TRANSDUCTION PRINCIPLE AND FREQUENCY RESPONSE.

Transduction principle	*Number of accelerometers*	*Classification by frequency response*
Capacitive	40	DC
Piezoresistive	15	
Resistive	7	
Optical	4	
Thermal	2	
Piezoelectric voltage output	30	AC
Piezoelectric charge output	20	

Resistive and especially optical and thermal accelerometers are not very common in contrast to the other transduction principles. Due to small samples, we will highlight only special characteristics of these three principles in the next section.

IV. ANALYSES OF PARAMETERS

In this section, we will analyze the parameters overload shock limit, measurement range, power consumption, volume, weight, frequency response, resonance frequency, and operating temperature of accelerometers specified on their datasheets.

A. Measurement range of accelerometers

In datasheets, the measurement range is mostly specified for a symmetric range of acceleration, e.g., -500 g to 500 g. Rarely the lower limit is restricted, e.g., -200 g to 500 g. In this review, the parameter measurement range stands for the positive upper limit of acceleration, for the last given example 500 g, because for 95 of 118 accelerometers, the measurement range is symmetric. For 24 accelerometers, the lower limit is not specified and only for one accelerometer, the lower limit is restricted. In Figure 1, the measurement range is plotted against the accelerometer-ID. A number of 118 different accelerometers have been analyzed, so there are 118 IDs where each ID is a unique identifier. That means an accelerometer, e.g., with the ID 50 in Figure 1 has the same ID in Figure 2 to Figure 8. These figures were designed to correlate the analyzed parameters among each other. Among 118 accelerometers, there are only three capacitive accelerometers with two measurement axes. Because of that small number, they were classified into the class of triaxial accelerometers, annotated in Figure 1.

Capacitive accelerometers are limited to a measurement range of 500 g and resistive accelerometers to 10×10^3 g. Only piezoelectric and piezoresistive accelerometers are capable of measuring more than 10×10^3 g with the restriction that piezoresistive accelerometers are the only ones capable of DC measurement above 10×10^3 g.

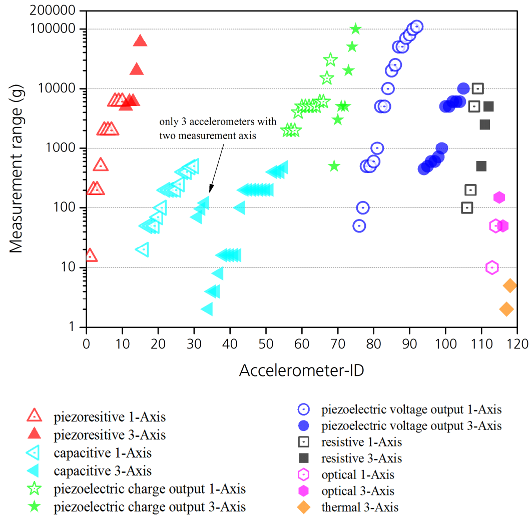

Figure 1. Measurement range of 118 accelerometers classified by transduction principle, number of measurement axis and sorted by measurement range in ascending order.

For measuring 100×10^3 g and more, uniaxial piezoelectric accelerometers are capable. However, triaxial piezoelectric accelerometers with voltage output are limited to 10×10^3 g.

B. Overload shock limit

Figure 2 presents the overload shock limit against the ID. Except for piezoelectric accelerometers, most accelerometers cannot be used for overload shock limits beyond 10×10^3 g. Especially the capacitive principle is strictly limited to the 10×10^3 g threshold.

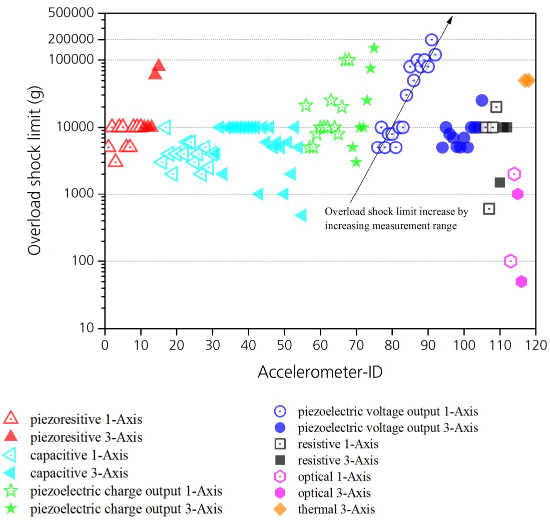

Figure 2. Overload shock limit of 118 accelerometers classified by transduction principle, number of measurement axis and sorted by measurement range in ascending order.

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The review also shows that a general comparison of overload shock limits for different accelerometers is only possible to a limited degree, due to the fact that this parameter is only valid for a specified profile of acceleration and a defined period of time. Usually, the overload shock limit is specified as the peak of a semi sinusoidal profile of acceleration. But a uniform specification of the period of time on datasheets is missing. The period of time is specified as the maximum or the minimum time or the rise time of a semi sinusoidal profile. For altogether 85 of 118 accelerometers, the period of time is not specified on their datasheets.

C. *Power consumption of accelerometers*

Figure 3 shows the power consumption against the ID. Note that piezoelectric accelerometers with charge output and optical accelerometers are excluded because electronics is not integrated and therefore no power is used. Of course, both principles also need electronics, but in this review, we did not focus on external electronics. Furthermore, for 13 of 118 accelerometers, no power consumption was specified on the datasheet.

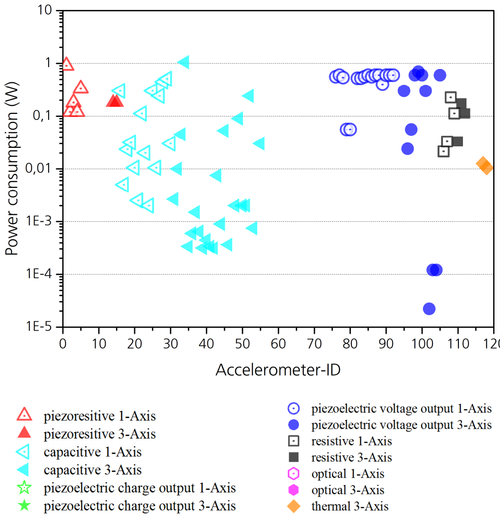

Figure 3. Power consumption of 81 accelerometers classified by transduction principle, number of measurement axis and sorted by measurement range in ascending order.

The upper limit of power consumption is about 1 watt. Generally, the majority of capacitive accelerometers show the minimal power consumption beside some piezoelectric accelerometers with voltage output. Our analyses show that there is no significant correlation between power consumption and measurement range. The power consumption for uniaxial piezoelectric accelerometers with voltage output is nearly constant.

D. *Volume of accelerometers*

Figure 4 illustrates the volume plotted against the ID. Note that the volume for piezoelectric accelerometers with charge output and optical accelerometers does not comprise integrated electronics as explained in the section before. The volume of capacitive accelerometers covers a range of five decades, but this transduction principle has the minimal volume in total. Tendentially, the volume of piezoresistive

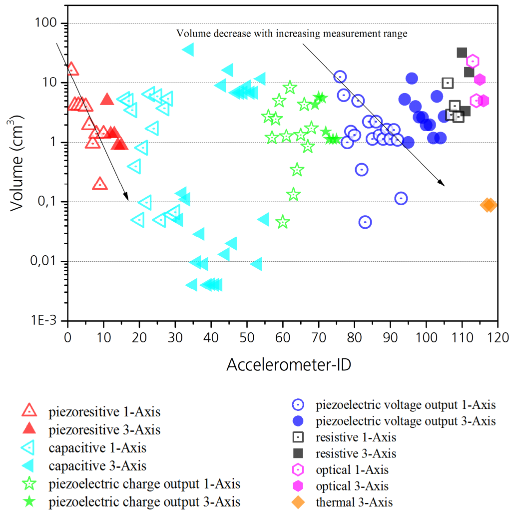

Figure 4. Volume of 118 accelerometers classified by transduction principle, number of measurement axis and sorted by measurement range in ascending order.

and piezoelectric accelerometers with voltage output decreases by increasing measurement range. However, optical accelerometers have the largest volume.

E. *Weight of accelerometers*

Figure 5 shows the weight plotted against the ID. For 18 of 33 capacitive and for the two thermal accelerometers, the weight is not specified on the datasheet. Note again that electronics for piezoelectric accelerometers with charge output and optical accelerometers are excluded.

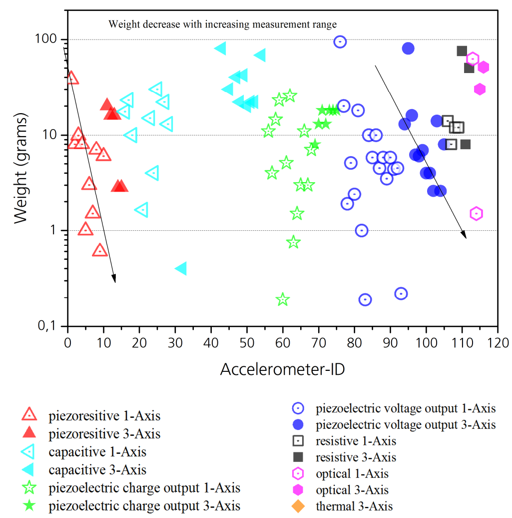

Figure 5. Weight of 98 accelerometers classified by transduction principle, number of measurement axis and sorted by measurement range in ascending order.

Almost all transduction principles cover a range of three decades from 0.1 grams to 100 grams. According to the volume, there is a clear tendency of decreasing weight with increasing measurement range for piezoresistive accelerometers and piezoelectric accelerometers with voltage output.

F. Resonance frequency of accelerometers

Figure 6 shows the resonance frequency plotted against the ID. For altogether 40 accelerometers (21 capacitive and 10 piezoresistive ones), this parameter was not specified on the datasheet. Due to sparse data, we exclude these two principles from discussion.

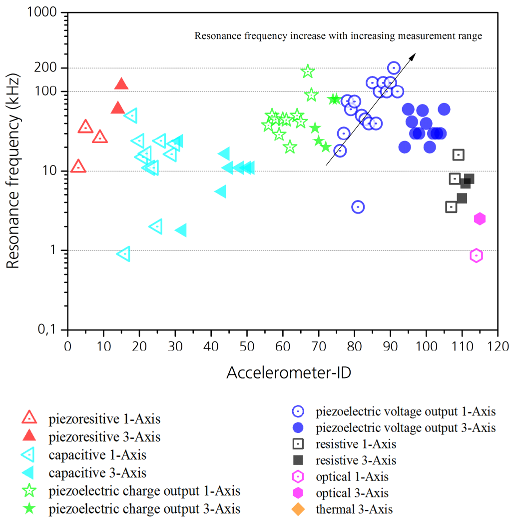

Figure 6. Resonance frequency of 78 accelerometers classified by transduction principle, number of measurement axis and sorted by measurement range in ascending order.

Tendentially, for uniaxial piezoelectric accelerometers with voltage output, the resonance frequency correlates with increasing measurement range and is limited to a range between 10 kHz up to 200 kHz. For triaxial piezoelectric accelerometers with voltage output, the maximum resonance frequency is significantly lower and limited to 80 kHz.

G. Frequency response of accelerometers

Figure 7 presents the range of the frequency response plotted against the ID. Notice that the axis of ordinate combines a logarithmic and linear scale. A comparison of the frequency responses of accelerometers is only possible to a limited degree because a uniform specification of the tolerance of the output signal on datasheets is missing. For only 54 of 118 accelerometers, the frequency response is specified for a tolerance of the output signal within ±3 dB. For 56 accelerometers, the tolerance for the output signal is specified non-uniformly, e.g., for -18 %, +15 %, ±10 %, ±7 %, ±5 %, ±10 dB, ±2 dB or not specified. For 8 accelerometers, the specification is completely missing.

With few exceptions, piezoresistive and resistive accelerometers are limited to 5 kHz and capacitive to 1 kHz. Most piezoelectric accelerometers are capable for a range of 1 Hz to 20 kHz, and a few are capable for a frequency response down to 0.2 Hz. By tendency, uniaxial piezoelectric accelerometers show a wider frequency response than the triaxial ones. The thermal accelerometers

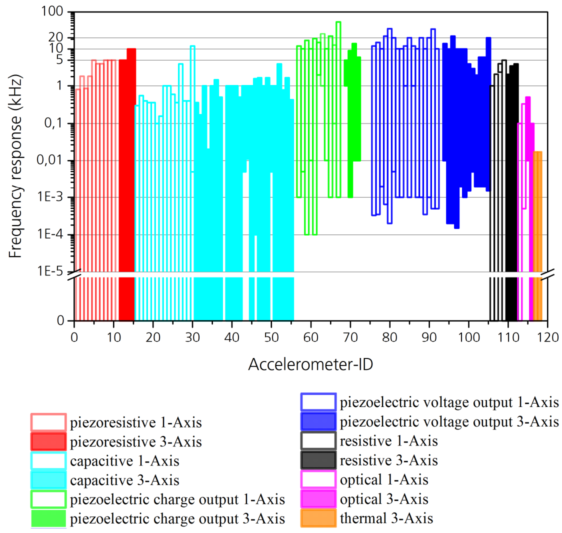

Figure 7. Range of frequency response of 110 accelerometers classified by transduction principle, number of measurement axis and sorted by measurement range in ascending order.

are limited to 17 Hz and by frequency extension circuits, this limit can be pushed to 100 Hz [10].

H. Operating temperature of accelerometers

Figure 8 presents the operating temperature against the ID. For piezoelectric accelerometers with charge output, the standard operating temperature is in the range of -54 °C to 150 °C. But they are capable to work up to 250 °C because

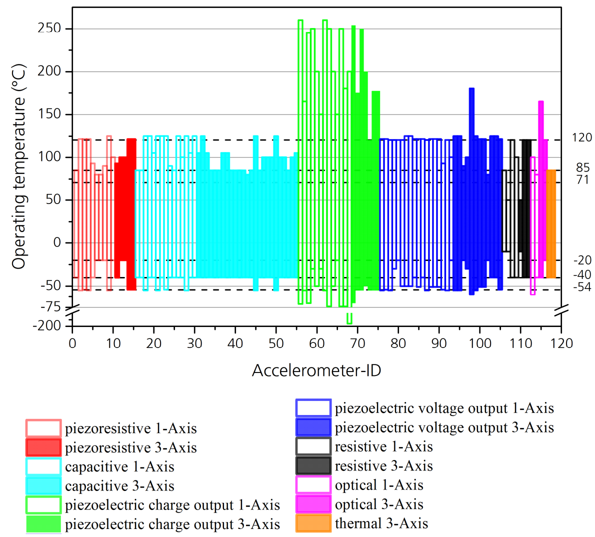

Figure 8. Range of operating temperature of 118 accelerometers classified by transduction principle, number of measurement axis and sorted by measurement range in ascending order.

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the electronics as limiting factor is excluded. In contrast, uniaxial piezoelectric accelerometers with voltage output are limited to a standard temperature of 120 °C. For capacitive accelerometers, the standard temperature is in the range of -40 °C up to 85 °C. For piezoresistive accelerometers, the standard temperature is only in the range of -20 °C up to 85 °C. By tendency, the positive operating temperature for the most uniaxial capacitive and piezoelectric accelerometers is higher than for the triaxial ones.

I. Performance of accelerometers by country of origin

For the last figure of this paper, we chose another design to illustrate two interesting facts. Therefore, a distinction between uniaxial and triaxial accelerometers has not been made. Figure 9 presents the overload shock limit plotted against the measurement range.

First, accelerometers from manufacturers of the European Union are limited to an overload shock limit of 100 x 10^3 g and to a measurement range of 80 x 10^3 g.

Second, there is a strict threshold for accelerometers based on a proof mass. Within a measurement range of up to 2 x 10^3 g, they are strictly limited to overload shock limits of 10 x 10^3 g. Remember that the thermal principle works without a proof mass, so it is less fragile to overload shocks.

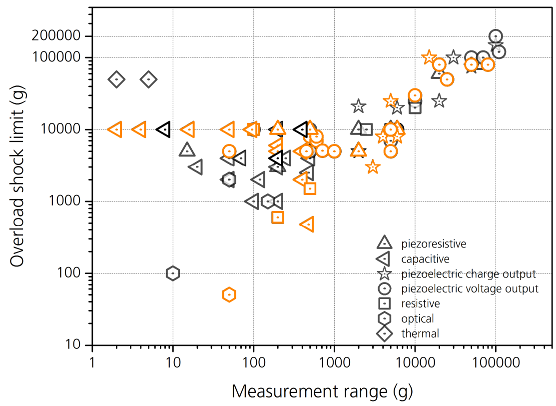

Figure 9. Overload shock limit versus measurement range of 118 accelerometers. The transduction principles are highlighted by the shape of the symbols. Accelerometers from the EU are highlighted in orange and the non-EU ones are highlighted in black.

Beside accelerometers capable of measuring more than 10 x 10^3 g, it is very difficult to find such with overload shock limits beyond the 10 x 10^3 g limitation.

V. CONCLUSION

A variety of commercial accelerometers have been analyzed. Performance and limits of accelerometers were presented and can be used as a reference work for choosing the right technology.

The paper shows that accelerometers from manufacturers of the European Union are nearly state of the art with regard to measurement range and overload shock limit. It was found a strict overload shock limit of 10 x 10^3 g for accelerometers with proof mass and a measurement range of up to 2 x 10^3 g.

We ascertain that the performance of uniaxial and triaxial accelerometers is slightly different. Especially uniaxial piezoelectric accelerometers show a better performance with regard to measurement range, overload shock, resonance frequency, frequency response and operating temperature than the triaxial ones.

A general comparison of accelerometer parameters is not always easy due to a lack of uniform or missing specification in datasheets. In this context, important parameters, such as overload shock limit, frequency response and resonance frequency are affected.

In summary, piezoelectric accelerometers show the highest measurement range, shock limits and operating temperature, capacitive accelerometers the lowest power consumption and volume, and piezoresistive accelerometers the widest frequency response.

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