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Review

Jerk in Earthquake Engineering: State-of-the-Art

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Abstract: The time derivative of acceleration, termed jerk, represents a physical property reflected through a sudden change of acceleration, and is expressed in m/s^3. Since jerk is felt by humans, it has been widely used as a common (dis)comfort parameter. In earthquake engineering, due to the inevitable need for further progress in understanding ground motions and soil, structural and non-structural responses, new frontiers need to be examined. Therefore, lately, there has been an increasing interest in jerk, and various research efforts have been made towards its applications. Since a proper overview of the jerk-related literature applicable to earthquake engineering is missing, the main purpose of this paper is to fill the gap and provide a starting point for future studies.

Keywords: jerk; acceleration; structure; non-structural component; equipment; response; control; damage; ground motion; sensor

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1. Introduction

The time derivative of acceleration, termed jerk (or jolt), represents a physical property reflected through a sudden change of acceleration, which is expressed in m/s^3. Since jerk is felt by humans, it has been widely used as a common (dis)comfort parameter (e.g., roads, rails, vehicles, trains, elevators, amusement rides). Its applications can also be found in the manufacturing of machinery, robots, and printers, as well as in space technology, global positioning systems, sports science, and so on. An extensive review of jerk considerations in science and engineering was provided in [1]. However, the list of referenced applicable studies on jerk in earthquake engineering is incomplete.

In earthquake engineering, motion quantities such as displacement, velocity, and acceleration have been commonly used, and over the years the state-of-knowledge on them has been constantly improved. Due to the inevitable need for further progress in understanding ground motions and soil, structural and non-structural responses, new frontiers need to be examined, in order to improve future generations of seismic design codes, so that the built environment is in line with contemporary changes. Lately, there has been an increasing interest in jerk, and various research efforts have been made towards its applications in earthquake engineering. Even though jerk is still not mentioned in codes for seismic analysis and design, in a report [2] it is mentioned as a relevant parameter for the performance-based seismic design of new buildings. On the other hand, jerk is defined in [3]–a standard related to mechanical vibration, shock, and condition monitoring, which is fully applicable to earthquake engineering.

The main goal of this paper is to provide an elaborate overview of all jerk-related literature applicable to earthquake engineering so that researchers can use it as a starting point for future studies. The paper is structured as shown in Figure 1, and as follows: structures and non-structural components are discussed in Section 2; structural control, isolation systems, and dampers are addressed in Section 3; ground motions and acceleration data are considered in Section 4; sensors and monitoring are reviewed in Section 5; a summary is provided in Section 6; and further research needs and conclusions are provided

in Section 7. It should be noted that some referenced sources cover more than one topic. So, in order to avoid repeating, they were placed into (sub)sections where, according to the authors' opinions, they fit best.

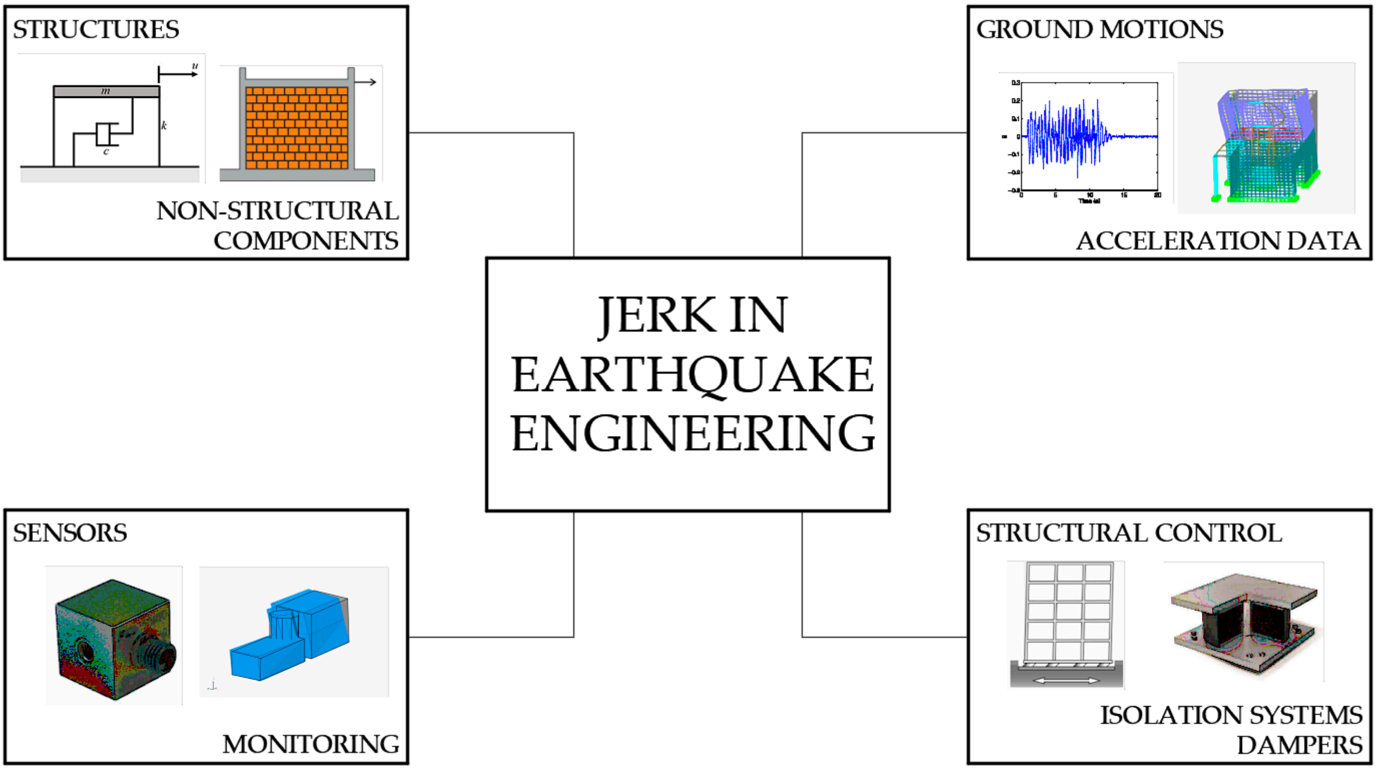

Figure 1. Graphical outline of jerk applications in earthquake engineering.

2. Structures and Non-Structural Components

2.1. Structures

The analysis of jerk on structures can be investigated from different points of view, considering the possible effects on the capacity and the characterization of demand. It is worth noting that the greater part of the available studies is released after numerical investigations (or in some cases, as further achievements made within other specific studies). Nevertheless, the response provided by specific real-scale tests and real-measurements can contribute to the main understanding of the problem. Also, an important aspect is related to the jerk influence on human perception and the possible discomfort of building occupants. This brief summary is developed in the following sub-sections, as a thread of different aspects that, however, are intrinsically related.

2.1.1. Structural Capacity: Response and Damage Analysis

The estimation of the residual life of structures represents an important issue since it is necessary to judge whether they can be used after being damaged by earthquakes. It was noted that during a strong earthquake the jerk response of a structure with bilinear restoring force has discontinuity, due to the rapid change from the elastic to plastic region. The method for the estimation of ductility factor by the wavelet analysis of absolute acceleration response was proposed in [4]. Starting from the necessity to know the ductility factor in order to estimate the cumulative structural damage, wavelet analysis was also used in [5] to examine jerk discontinuity at yield point for single-degree-of-freedom (SDOF) structures with bilinear restoring force subjected to filtered white noise excitation. The relationship between the velocity at the yield point and the ductility factor was derived based on the energy balance.

In general, some studies are available in the scientific literature, aiming to describe the jerk effects on reinforced concrete (RC) and masonry buildings. With regard to the latter, the resistance of masonry reinforced with polymer grids to jerks was discussed in [6,7], and it was stated that earthquakes (mainly strong ones) are dangerous for masonry buildings because jerks may crush bricks or even cause dislocations of some structural members. A simple method for checking the unbalanced bodies supported by buildings exposed to seismic jerks was proposed in [8]. The method was evaluated on two example buildings by comparing shear demands and capacities. Between the two buildings, one was a masonry church with two steeples and the analysis of the jerk suggested that there was a lack of balance between structural parts. The seismic response of vernacular masonry buildings was discussed in [9], and it was stated that one of the reasons for their vulnerability to seismic jerks is due to the slenderness of steeples, whose mass is much smaller than the mass of church bodies. It was also noted that lessons learned from vernacular heritage are of great value, particularly in the case of three-lobed churches, whose expected safety and durability can be reached by an appropriate shaping of the church bodies and by the proportionate sizing of steeples. In [10] it was stated that seismic jerk represents the fundamental component of the impulsive actions associated with the high-frequency content of seismic motions. Jerk effects and local failures in masonry structures were studied, and it was found that the monitoring of jerk in three directions may provide more significant information on damage compared to the inter-storey drift monitoring. Three-lobed churches exposed to earthquake actions were examined in [11] and, among others, jerk effects were discussed. It was concluded that in the case of steeples, seismic jerks often occur.

With regard to RC buildings, one of the example buildings mentioned in [8] was a spatial RC building with a pergola at its top, and similar observations were made as in the case of the masonry building. The possibility of using jerk as a ground motion intensity measure was presented in [12], by performing a nonlinear time-history analysis of several typical RC frame buildings with different numbers of storeys, exposed to two sets consisting of 7 and 27 ground motions. By applying a machine learning technique, it was found that for structures with low nonlinearity, jerk-based parameters were effective. Three-dimensional (3D) temporal characteristics of the responses of an RC frame building exposed to both the main shock and the largest aftershock of the Wenchuan earthquake were presented in [13]. It was stated that this was the first time that jerks of both the ground shaking and structural responses were recorded during an earthquake event. It was observed that peak accelerations agreed well with those calculated by integrating recorded jerks. The obtained results provide useful information for further studies. The influence of jerk on the responses of rigid linear elastic and nonlinear (elastic-perfectly-plastic and stiffness degrading) SDOF systems exposed to a strong ground motion was studied in [14]. It was found that jerk practically "announces" nonlinear behaviour, which might be of interest in damage analysis and structural health monitoring.

By using a new concept termed jerk energy, two damage localization procedures were proposed in [15]. The procedures are based on the difference in the jerk energy curvature. Their efficacy was validated both numerically and experimentally, i.e., a ten-degree-of-freedom mass-spring-damper system was considered numerically, and a laboratory-scale 6-storey shear building was experimentally examined. It was shown that the procedures perform well in the presence of noise. The above-mentioned concept of jerk energy was used in [16] to establish a correlation between global and local damage to RC structures exposed to strong earthquakes. It was stated that the relative contribution of local to global damage should be described from three aspects: static structural information or configuration, dynamic inter-storey drift, and dynamic energy information. By using jerk energy and sensors, a finite element method for structural damage identification was proposed and checked on a bridge structure [17]. A method for the determination of a damaged storey in an RC 4-storey shear frame structure with ambient vibrations was presented in [18], and it was based on a modified jerk energy methodology. The damage

was taken as a localized reduction in the stiffness of a structural member. It was shown that the proposed algorithm has effectively detected the damage existence.

Criteria for the detection of nonlinearity in the restoring force were provided in [19], by using the time derivative of jerk (the second time derivative of acceleration) termed snap, and a method for the detection of damage due to the change in structural stiffness was also presented. Afterwards, a method for the estimation of plastic deformation of a bilinear elasto-plastic SDOF system using jerk and snap was proposed [20,21], and it was stated that the onset of yielding can be detected by using snap, whereas jerk can be used to calculate the plastic deformation after yielding. The method was extended in [22], by determining the mathematical relation between snap and stiffness change, and the velocity of the system. The mathematical model was verified by performing the dynamic analysis of an undamped bilinear SDOF models with sharp and rounded yield points, different natural periods, and post-yield stiffness. By using radial basis functions (RBFs), a numerical method for solving structural dynamic responses, including jerk, was proposed in [23]. Within the method, there were no assumptions of load changes and acceleration in a time interval. Among others, the method was applied on a 3-storey linear elastic planar frame structure exposed to seismic action. First, the basic equation of motion was considered:

$$M\ddot{X} + C\dot{X} + KX = -M\ddot{X}_g(t) \tag{1}$$

where M, C and K are the mass, damping and stiffness matrices, respectively, $\ddot{X}$, $\dot{X}$ and X are the relative acceleration, relative velocity and relative displacement vectors, respectively, and $\ddot{X}_g(t)$ is the ground acceleration vector.

Under the assumption that $\ddot{X}_g(t)$ is derivable, the following can be obtained:

$$M\dddot{X} + C\ddot{X} + K\dot{X} = -M\dddot{X}_g(t) \tag{2}$$

where $\dddot{X}$ is the relative jerk vector, and $\dddot{X}_g(t)$ is the ground jerk vector.

Since the absolute jerk $\dddot{X}_{abs}$ is of interest, Equation (2) was transformed into Equation (3). The proposed RBF numerical method was used to determine several motion quantities, including absolute jerk.

$$M\dddot{X}_{abs} = -C\ddot{X} - K\dot{X} \tag{3}$$

It was also noted that commonly used numerical methods such as Newmark and Wilson-θ methods shall not be used for solving Equation (3), due to the assumptions involved in them. The same was also observed in [24,25], where the fourth-order Runge-Kutta method was pointed out as a good option since it is stable, and the smoothness of the signal is completely considered.

A solution to Equation (2) was also proposed in [24,25], by using the state space method, and by introducing system state vectors $W = \left\{X, \dot{X}, \ddot{X}\right\}^T$ and $Z = \left\{X, \ddot{X}, \dddot{X}\right\}^T$. Thus, Equation (2) was then expressed in the form of state equations:

$$\dot{W} = FW + G\dddot{X}_g(t) \tag{4}$$

$$Z = HW + J\dddot{X}_g(t) \tag{5}$$

where matrices F, H, G and J were defined as:

$$F = \begin{bmatrix} 0 & I & 0 \\ 0 & 0 & I \\ 0 & -M^{-1}K & -M^{-1}C \end{bmatrix}, H = \begin{bmatrix} I & 0 & 0 \\ 0 & 0 & I \\ 0 & -M^{-1}K & -M^{-1}C \end{bmatrix}, G = J = \begin{bmatrix} 0 \\ 0 \\ -I \end{bmatrix} \tag{6}$$

The other option to obtain jerk is to apply difference methods to acceleration data. In the central difference method, jerk can be determined as:

$$j(t_i) = \frac{a(t_{i+1}) - a(t_{i-1})}{2\Delta t} \quad (7)$$

where $a(t_i)$ is the acceleration and Δt is the time interval between two neighbouring points. Clearly, $j(t_i)$ represents an average jerk in the interval $2\Delta t$ between points $i - 1$ and $i + 1$.

The forward and backward differences can be described with Equations (8) and (9), respectively:

$$j(t_i) = \frac{a(t_{i+1}) - a(t_i)}{\Delta t} \quad (8)$$

$$j(t_i) = \frac{a(t_i) - a(t_{i-1})}{\Delta t} \quad (9)$$

The results obtained from Equations (8) and (9) are essentially the same since they are only shifted for Δt, whereas Equation (7) produces slightly (mainly negligible) lower values of jerk peaks.

Finally, to the authors' best knowledge, in no earthquake engineering-related studies jerk was imposed on the basic equation of motion (i.e., Equation (1)). Since the forced-based design is still the most widely used approach for the seismic design of structures and non-structural components, changing the equation of motion by introducing jerk to it would be a fundamental change to the analysis and design philosophy, which would impact the current states of the art and practice.

2.1.2. Seismic Demand: Jerk Response Spectra

The concept and characteristics of seismic jerk response spectra were presented in [24], and the solution method of elastic and inelastic jerk spectra was established. The impact reduction factor was also presented, and it was defined as the ratio of the maximum jerk of a SDOF elastic system and the maximum jerk of an inelastic system with the determined displacement ductility. It was shown that jerk influences buildings with short and middle periods, whereas its influence on long-period structures can be ignored. The study was later expanded [25], and the characteristics of absolute jerk response spectra for elastic and inelastic SDOF systems by considering different site conditions and ductility of the elastic-perfectly-plastic model (used to simulate SDOF inelastic systems) were examined. It was shown that, in general, absolute jerk and acceleration spectra have similar characteristics. The impact reduction factor was again discussed and, compared to the well-known strength reduction factor, it was shown that it does not depend on the natural period.

Jerk response spectra were also studied in [26], and formulas and graphs for their determination were proposed. However, the proposals were not supported by any means (e.g., parametric time history analysis). It was stated that jerk spectra should be taken into account among other response spectra within structural design for dynamic loading, including earthquake impact. In a later study [27], a jerk response spectrum was plotted on the same graph with displacement, pseudo-velocity, and pseudo-acceleration spectra. By considering the Eurocode 8 pseudo-acceleration spectra [28], it was stated that the jerk-sensitive region corresponds to natural periods smaller than T_B (i.e., the lower limit of the period of the constant spectral acceleration branch). Relative jerk spectra of inelastic SDOF systems modelled by bilinear, Ramberg-Osgood and Takeda hysteresis rules were calculated in [29]. A set consisting of 27 ground motions was used for analysis, various natural periods, damping values, and yield strengths were taken into account, and an empirical formula for the estimation of jerk in inelastic SDOF systems was proposed. Unfortunately, a possible application of the obtained results is very limited since relative instead of absolute jerk spectra were considered.

For the purpose of this paper, a brief analysis of absolute jerk spectra was performed, by using a set of 30 ground motions, with the mean peak ground acceleration (PGA) of 0.43 g. More details on the set and its selection criteria are given in [30], where it was

recently used, and the detailed data of the selected records are available in [31]. In short, the set corresponds to the Eurocode 8 Type 1 spectrum for soil B, with the upper limit of the period of the constant spectral acceleration branch T_C = 0.5 s.

The elastic absolute jerk spectra, S_j, corresponding to individual records, are shown in Figure 2. Spectra were calculated by applying the backward difference method, i.e., Equation (9), and by considering 5% damping. The mean value of the absolute jerk spectra is also provided. From Figure 2 it can be seen that the peak value of the mean absolute jerk spectrum is 48.7 g/s and that the peak-related zone is approximately located between 0.04 and 0.06 s. In addition, jerks larger than 10 g/s can be seen all the way up to almost T = 0.5 s (accidentally equal to T_C). The latter two observations indicate that jerks may be of interest in rigid structures, and generally in the case of higher vibration modes having short periods. The mean peak ground jerk (PGJ) amounted to 17.8 g/s, meaning that its amplification, with the respect to the peak jerk value of 48.7 g/s, was 2.7. Jerk peaks of some motions are very large, with the maximum of almost 249 g/s obtained for the 7162y, which is the transversal component of the Firuzabad earthquake that happened on 20 June 1994 in Iran. According to the data from the European Strong-Motion Database, the fault mechanism was strike-slip, the magnitude Mw was 5.9, the epicentral distance was 7 km, and the PGA was 1.06 g. Due to its specific characteristics, the same record was used in the above-mentioned study [14].

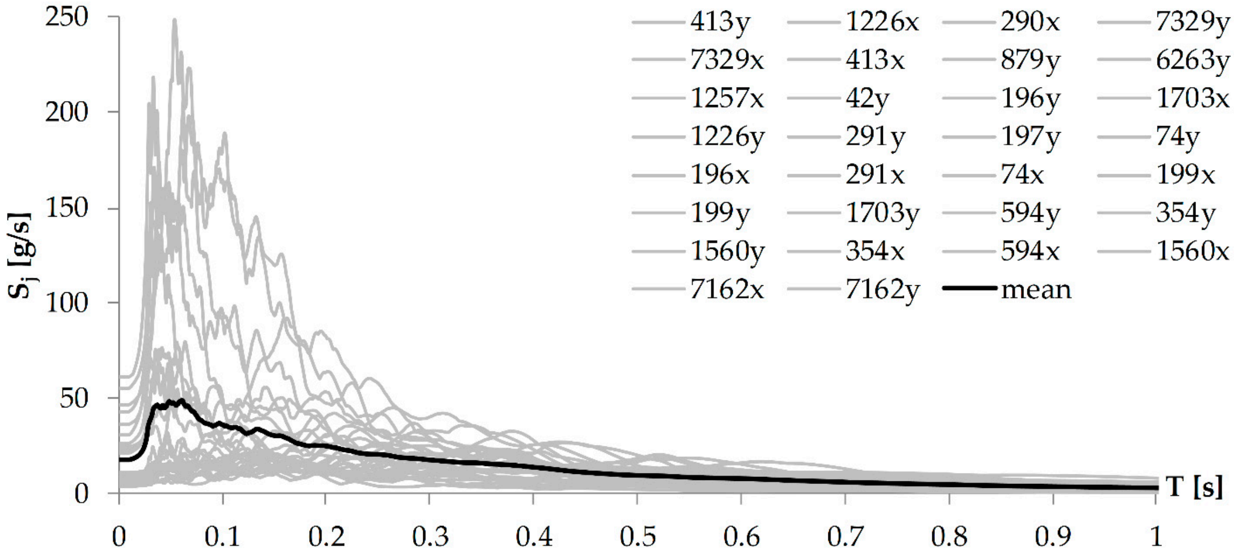

Figure 2. Elastic absolute jerk spectra of individual records and their mean spectrum, all obtained for 5% damping.

In [25] it was shown that pseudo- and absolute jerk spectra are significantly different if the former is determined by multiplying absolute acceleration spectra, S_a, with angular frequency ω. Here, this finding was re-examined, and the obtained results are presented in Figure 3. Namely, Figure 3 shows the ratio of absolute jerk and absolute acceleration spectra, along with ω throughout the whole period range. It can be seen from Figure 3a that the ratio S_j/S_a and ω agree well between T = 0.4 s and T = 1.0 s. For T < 0.4 s the differences increase towards T = 0 s, where ω tends to infinity, whereas for T > 1.0 s the differences increase toward longer periods, with an obvious separation after T = 4.0 s (Figure 3b), which in terms of Eurocode 8 actually represents the limit for long period structures. Thus, the obtained results confirm the finding provided in [25]. It is clear that specific equations for the estimation of pseudo-jerk from the absolute acceleration spectra are needed for practical purposes, which should be based on extensive parametric studies.

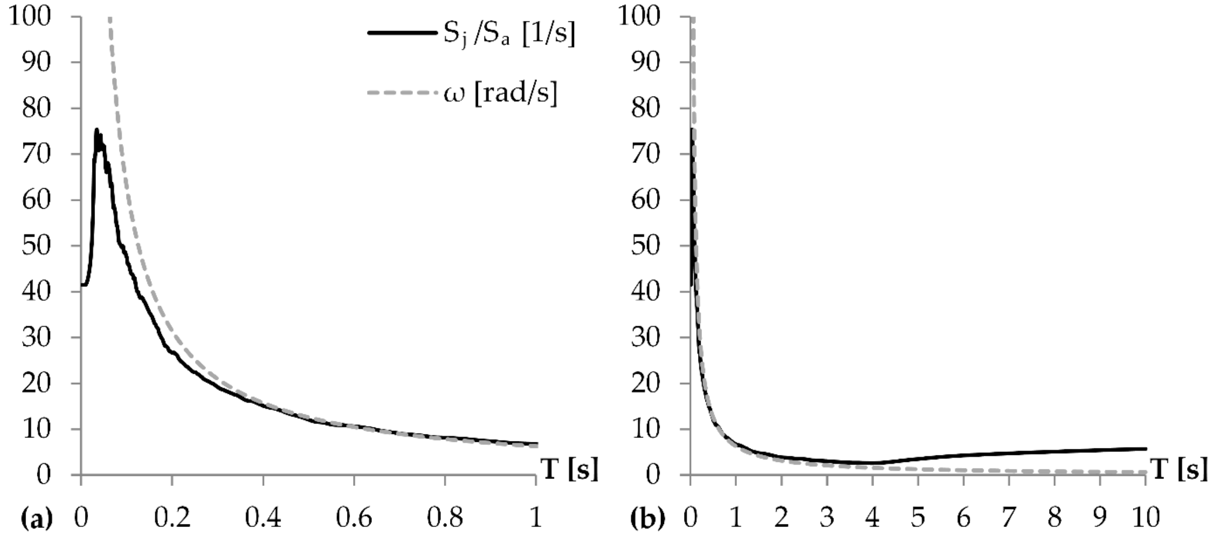

Figure 3. The ratio of S_j/S_a and ω up to and including (**a**) T = 1.0 s and (**b**) T = 10.0 s.

2.1.3. Testing and Observations from Real Measurements

The use of real-measurements to identify the behaviour of structures and the effective forces acting on them is the main means to understand structural engineering problems. When talking about seismic behaviour of structures, most of the information is provided by the monitoring of existing structures and infrastructures, on which it is possible to place monitoring systems for predicting the elastic dynamic behaviour (e.g., [32,33]) or the occurrence of damage (e.g., [34]). Generally speaking, starting from the fact that large-scale testing and qualification of structural systems and their components is crucial for the development of earthquake engineering knowledge and practice, jerk was used within the development of a new earthquake engineering real-time distributed hybrid testing method [35]. The proposed technique enables geographically distributed scientific equipment to be coupled in real-time. New large time-step prediction algorithms were used, capable of overcoming both local actuation and distributed system delays. Application of the jerk feedback for the shake table testing was presented in [36], and it was concluded that more testing is needed. Afterwards, the previous work was expanded in [37], and a jerk-based new shake table control technology was proposed by introducing both jerk feedback and feed-forward into the controlling unit on the basis of the three-variable control algorithm.

2.1.4. Effects of Jerk on the Human Comfort

Human comfort due to the seismic events was only scarcely mentioned in the available literature since most studies aim to describe structural behaviour or seismic demands in buildings and their assets, but often neglect the human perception of such events [38]. Consequently, with regard to seismic jerk, very few studies are available in the scientific literature. Namely, in [39] it was briefly noted that it is generally accepted that acceleration and jerk are the main causes of human discomfort, while in [40] it was stated that human response to a building motion is a complex phenomenon, and that building motions can be described by various physical quantities, including jerk.

2.2. Non-Structural Components (NSCs)

Over the last decade, the interest in the behaviour of NSCs under earthquake actions has grown extensively, and a notable number of NSC-related studies were published (e.g., see [41]), as well as those dealing with the seismic input that needs to be considered in the NSC design (e.g., [42]). Apparently, the first time that jerk was briefly mentioned in earthquake engineering-related studies was in a technical report [43], where an approach for the direct

generation of floor response spectra in classically and non-classically damped linear systems was developed. Performance-based seismic engineering and design were reviewed and discussed in [44], and it was noted that for the control of NSC and content damage it may be necessary to limit a combination of inter-storey drift, floor velocity, floor acceleration, and even jerk in cases of frequent earthquake ground motions.

The effect of the stick-slip (jerking) motion on the sliding problems in structural and earthquake engineering applications (e.g., the response of unanchored NSCs, base-isolated structures, and geotechnical structures) was investigated in [45]. It was demonstrated that the implementation of simplified sliding models may result in underestimation of the sliding response. An interesting study on the energy transfer from the fundamental to higher modes of vibration during a nonlinear response was performed in [46], and a low-amplitude sinusoidal excitation containing a sudden jerk was used as the shake table input motion. Scaled single-bay 3-storey moment resisting steel structural frame was considered, both with fixed base and with sliding isolators. In addition, a SDOF NSC component was attached to the second floor, and its frequency was tuned to the second mode of the structure. By examining recorded floor accelerations and NSC responses, it was found that an energy transfer from the fundamental mode can occur due to a sudden change in structural stiffness. A summary of the abovementioned works is reported in Table 1.

Table 1. Seismic jerk in structures and non-structural components.

Field of Application	Reference	Motivation
Structural capacity	Segawa et al. [4]	Estimation of ductility factor by wavelet analysis of absolute acceleration response
	Segawa et al. [5]	Estimation of ductility factor studying jerk discontinuity at yield point in a SDOF system
	Sofronie [6,7]	Effect of jerk in masonry buildings
	Sofronie [8]	Effect of jerk in two case studies (masonry and RC buildings)
	Sofronie et al. [9]	Effect of jerk on a vernacular masonry building
	Mariani and Pugi [10]	Local and global failures due to jerk in masonry structures
	Irimia [11]	Effect of jerk on masonry churches and influence on steeples damages
	Yaseen et al. [12]	Use of jerk as an intensity measure
	Dai et al. [13]	Influence of jerk on an RC frame building
	Vukobratović [14]	Influence of jerk on rigid linear elastic and nonlinear SDOF systems
	An et al. [15]	Damage identification through jerk energy
	He and Xu [16]	Correlation between local and global damages through jerk energy
	Mohamed et al. [17]	Damage identification on a bridge structure through jerk energy
	Mehboob and Zaman [18]	Damage detection method on an RC building based on ambient vibrations and jerk energy method
	Wakui et al. [19]	Detection of nonlinearity in restoring forces and damage
	Wakui and Iyama [20] Wakui et al. [21]	Estimation of plastic deformation in SDOF systems
	Iyama and Wakui [22]	Mathematical model to relate jerk to stiffness variation
	Li et al. [23]	Numerical method for structural dynamic problems using jerk

Table 1. *Cont.*

Field of Application	Reference	Motivation
Seismic demand	He et al. [24,25]	Jerk response spectra and analytical solution
	Taushanov [26,27]	Jerk response spectra
	Papandreou and Papagiannopoulos [29]	Relative jerk spectra of inelastic SDOF systems
Testing and observations from real measurements	Ojaghi et al. [35]	Development of a new real-time distributed hybrid testing method
	Li et al. [36]	Observed jerk from a shake table test
	Li et al. [37]	Development of a jerk-based shake table control technology
Human comfort	Yalla et al. [39]	Demonstration of jerk as source of human discomfort
	Mishra and Dubey [40]	Human response to seismic jerk
NSCs	Sharma and Sing [43]	Jerk effect on NSCs
	Bertero and Bertero [44]	Jerk as a control parameter for NSC damage
	Nikfar and Konstantinidis [45]	Effect of the stick-slip (jerking) motion on NSCs
	Chakraborty and Ray-Chaudhuri [46]	Study of energy transfer among vibration modes, accounting for jerk contribution

3. Structural Control, Isolation Systems and Dampers

3.1. Structural Control

The use of control systems can provide a significant contribution to the reduction of the overall response of civil structures and infrastructures that are subjected to seismic actions. Among the main available control systems, the scientific literature provides active and semi-active methods, using, for example, hydraulic systems of smart fluids [47]. With regard to seismic jerk, research focused on the control of total structural jerk in order to minimize response and damage in structures subjected to large seismic events was performed in [48]. An optimal regulator method was proposed and the results showed that the control approach is effective for near-field events characterised by large impulses. A performance-based semi-active control algorithm for base-isolated buildings exposed to near-fault earthquakes was developed in [49,50]. It was proven both in jerk reduction and controlling of different responses for different levels of ground shaking, and the results showed that the algorithm is successful in improving structural and NSC performance of isolated buildings.

A new model-based servo-hydraulic tracking control method to achieve accurate tracking of displacement in real time was proposed in [51], and jerk was considered within the study. The efficacy of the proposed approach was demonstrated through real-time hybrid simulations for a SDOF system and a 9-storey steel building. Jerk was also considered in the report on structural control strategies for earthquake response reduction of buildings [52]. The focus of the report was the improvement and the validation of semi-active control strategies for building protection from severe earthquakes.

A control algorithm with the potential to prevent structures from experiencing significant jerks under earthquakes with significant high-frequency components was proposed in [53]. It was designed to produce a negative stiffness friction damping force with a gradual change at velocity switches. The performance of an active control system employing the algorithm was demonstrated by applying seismic excitations to a benchmark base-isolated structure. The findings of the study might be beneficial to the sensitive high-frequency equipment within buildings.

Jerk was considered within a proposal of an adaptive gain scheduled semi-active vibration control using an artificial neural network [54]. In order to design it with high control performance against earthquakes with different time and/or frequency properties, multiple semi-active control laws with high performance for each of the multiple earthquake disturbances were scheduled in an adaptive manner. The proposed design method was applied to the semi-active control design of a base-isolated building with a semi-active damper.

3.2. Isolation Systems

Base isolation systems are the most extensively used systems to separate a building from the ground, allowing only horizontal movements of the foundation. The main aim is to decrease the seismic loading action by means of isolation devices in between the endpoint of the foundation and the starting point of the column section. In general, the most commonly used isolation systems in the practice are rubber base and friction pendulum, and several scientific works proposed intensive studies of the former (e.g., double concave [55] or triple concave [56]), and the latter (e.g., [57]) types. Regarding the design of isolation systems, few studies reported jerk-related aspects. As a matter of fact, although not explicitly used in the design of displacement control and uplift restraint device for base-isolated structures in [58], jerk was mentioned in the context that the device action prevented its sudden occurrence. The device was tested within a 9-storey one-quarter scale steel structure isolated using eight multilayer elastomeric bearings, and the system was subjected to a large number of earthquakes. Optimum viscous damping for the response of base-isolated structures was investigated in [59], and the criterion was the minimization of peak floor accelerations. Within the investigation, among other quantities, jerk was also used. Afterwards, a formulation for earthquake-resistant design of an optimum hybrid isolation system for the peak acceleration reduction (i.e., for the protection of sensitive equipment) was presented in [60]. It was noted that when a mean peak acceleration response of equipment is of interest, the evaluation of its jerks becomes necessary. This observation is important for the analysis and design of NSCs in buildings.

3.3. Dampers

Seismic dampers are systems designed for protecting structures and their integrity, by means of the capacity to absorb input energy given by earthquakes, i.e., by reducing structural forces and displacements. Several kinds of dampers have been used over the years, such as viscous (e.g., [61]), viscoelastic (e.g., [62]), friction (e.g., [63]), yielding (e.g., [64]), magnetic (e.g., [65]) and tuned mass (e.g., [66]) dampers. In this case also, few studies reported information on jerk. For example, various techniques for the mitigation of building motions were discussed in [67], and passive and active damping devices for improving the performance of tall buildings exposed to wind and seismic loads were considered. It was stated that basing perception criteria on jerk would better capture the stimulus which defines the human perception of a random motion. Semi-active smart-dampers for multi-level seismic hazard mitigation of steel moment resisting frames were considered in [68]. Within the study, it was observed that structural jerk may be closely related to the damage to people and equipment within a building subjected to seismic events, and it was used as a measure to assess structural performance. Based on the observation of jerk from the acceleration response history in [69], it was found that a series coupled damper system is effective against ground motions. The relative performance of the coupled units has been studied on a 3D RC frame structure. The time history analysis of the structural system with coupled damper units, uncoupled damper units and without any supplemental damping showed that the structural response of the former was most favourable in terms of storey displacement and drift. A summary of the abovementioned works is reported in Table 2.

Table 2. Seismic jerk in structural control.

Field of Application	Reference	Motivation
Structural control	Chase et al. [48]	Control of total structural jerk, minimizing damage in structures subjected to large seismic events
	Mehrparvar and Khoshnoudian [49] Khoshnoudian and Mehrparvar [50]	Proposal of a performance-based semi-active control algorithm for base-isolated buildings
	Phillips and Spencer, Jr. [51]	Proposal of a new model-based servo-hydraulic tracking control method
	Asai and Spencer, Jr. [52]	Jerk as a structural control parameter for earthquake response reduction of buildings
	Gong and Xiong [53]	Proposal of a control algorithm to prevent structures from significant jerks
	Hiramoto et al. [54]	Proposal of an adaptive gain scheduled semi-active vibration control
Isolation systems	Griffith et al. [58]	Jerk in the operation of a seismic device
	Inaudi and Kelly [59]	Definition of optimum viscous damping in the response of base-isolated structures
	Inaudi and Kelly [60]	Proposal of a formulation for optimum hybrid isolation systems
Dampers	Kareem et al. [67]	Jerk as a perception criterion of seismic motion
	Hunt [68]	Jerk as measure to assess structural performance in steel buildings with semi-active smart-dampers
	Sinha et al. [69]	Study on a series coupled damper system against jerk action

4. Ground Motions and Acceleration Data

When talking about seismic actions, one of the main issues in the analysis is the input definition, as well as the ground motions selection. Several studies about the topic have been provided, from the compatibility with the code spectrum for a given limit state (e.g., [70]) up to the properties of efficiency and sufficiency that must characterize the suite of ground motions [71]. Although different techniques are available in the literature, ground motions can be selected according to the intensity measures, as for example shown in [72]. Even in the case of seismic jerk, a possible challenge would be the definition of this measure as a parameter for quantifying seismic demand. With this regard, a brief mention of jerk can be found in [73], where the prediction of design response spectra using ground characteristics was performed. Jerk was used in a study of the temporal 3D characteristics of the 1995 Kobe earthquake records [74]. Based on the obtained findings, further quantitative descriptions of ground motion characteristics were provided in [75], and the study implied that the derivatives of acceleration might be of interest. Based on the analysis of 3D temporal characteristics of the Chi-Chi earthquake ground motions in [76], it was stated that acceleration pulses are a very useful and interesting phenomenon. Afterwards, the effects of pulse-dominant excitations on the peak responses of SDOF systems were studied [77]. Special attention was given to the effect of pulse sequences and near-field ground motions, which cause damage different from the one caused by far-field motions. In [78] it was found that jerk, which was termed time derivative of acceleration (TDoA), was noticeably large in the near-field area during the Chi-Chi earthquake. When it comes to structural response, it was stated that a large TDoA associated with strong acceleration may result in inhomogeneous dynamic loading and may cause stress concentration and local damage. Real-time algorithms for jerk estimation from noisy acceleration data were discussed in [79], and a model-based estimation technique was proposed by considering jerk behaviour through a random walk process.

A novel method of Bayesian learning using automatic relevance determination prior to an application to earthquake early warning was presented in [80]. The method was applied to classify ground motion data, which is needed in the development of early warning systems for large earthquakes. Besides acceleration, velocity, and displacement, the values

of jerk were taken into account. Jerk was also used in [81] for the development of software for an on-site warning home seismometer. It was found that the algorithm can correctly distinguish between noise and earthquakes.

In [82] it was recognized that jerk represents a measure of ground motion, and it was used to identify noise in accelerograms. Jerk was used for the elimination of spikes in strong motion records in [83], as well as in [84] to identify spikes in strong motion records with strange waveforms. Jerk was also considered within the identification of unrealistic spikes in acceleration response histories obtained during the shake table full scale experiment on a multi-storey building [85].

Finally, within the evaluation of the performance of a high-rate Global Positioning System (GPS) based on observations from shake table tests and the 2010 Chile earthquake [86], it was found that errors in measuring coincided with large accelerations and jerks, which can cause GPS units to temporarily lose tracking on satellite signals. A summary of the abovementioned works is reported in Table 3.

Table 3. Seismic jerk in ground motion features definition and for acceleration data analysis.

Field of Application	Reference	Motivation
Ground motions and acceleration data	Malushte [73]	Jerk in the prediction of design response spectra
	Tong and Lee [74]	Use of jerk in the study of temporal 3D characteristics of the 1995 Kobe earthquake records
	Tong et al. [75]	
	Dai et al. [76]	Use of jerk in the study Chi-Chi earthquake ground motions
	Dai et al. [77]	Effect of jerk (pulse-dominant excitations) on peak responses of SDOF systems
	Tong et al. [78]	Jerk (TDoA) defined as inhomogeneous dynamic loading and a cause of stress concentration and local damage
	Nakazawa et al. [79]	Development of real-time algorithms for jerk estimation
	Oh et al. [80]	Jerk in the field of earthquake early warning
	Horiuchi et al. [81]	Development of software for an on-site warning home seismometer
	Boore and Bommer [82]	Jerk as a measure of ground motion (identification of the noise in accelerograms)
	Zhou et al. [83]	Application of jerk to remove spikes from strong motion records
	Zhou et al. [84]	
	Fahnestock et al. [85]	Jerk used for identifying unrealistic spikes in acceleration response obtained during a shake table test
	Wang et al. [86]	Application of jerk as a parameter for quantifying errors in a High-Rate Kinematic GPS

5. Sensors and Monitoring

Another field of application of jerk is the vibration control of structures, which is recently, extensively employed in existing structures for the purpose of structural health monitoring. Several studies on structural monitoring can be found in the scientific literature, about structures (e.g., [87,88]) or infrastructures (e.g., [89,90]). For the case at hand, seismic jerk could be employed in sensors developed for structural health monitoring, especially in terms of an indicator of the motion change (e.g., up-down of an elevator). An example of a sensor that uses jerk as its control input was developed in [91,92], and the characteristics of a vibration-control system which applied the sensor for direct jerk-feedback control were evaluated. As a control model, a SDOF of freedom servo system was used, and a comparison of the analytical and experimental approaches indicated that the sensor operated correctly. An example of a jerk sensor is reported in Figure 4, as proposed in [92].

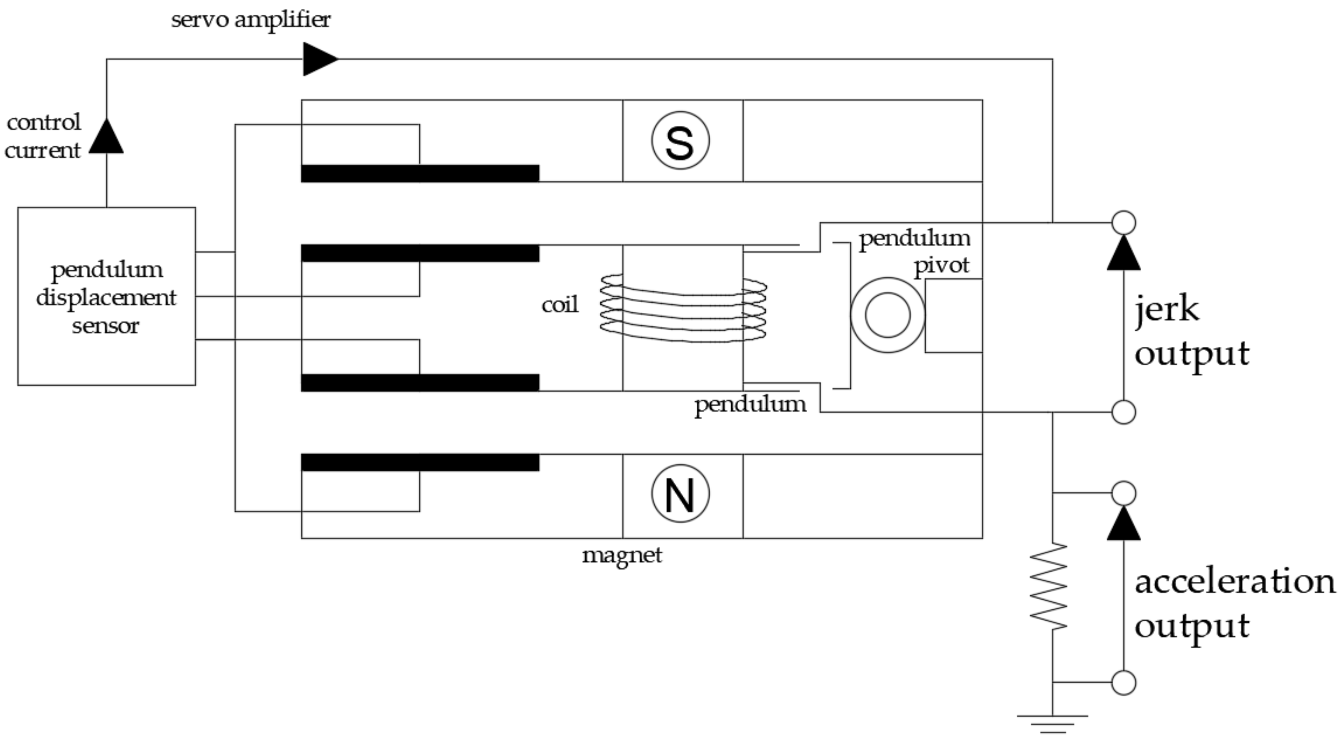

Figure 4. An example of jerk sensor, according to the proposal in [92].

The detection of discontinuities in building response to an earthquake by using a jerk sensor combined with a vibratory gyroscope and a cantilever was presented in [93]. The discontinuities that occurred between the elastic and plastic regions were detected by using wavelet analysis. The effectiveness of the sensor was proven through experimentally obtained results.

A sensor for the measurement of the time derivative of jerk (snap), was developed in [94], and its capability to detect local damage in structural members was investigated through low cycle fatigue tests. Additional fracture tests were performed to obtain the correlation between the measured jerk-dot and crack depth, and the results suggested that the sensor could provide an early alert before a substantial crack increase.

A jerk-measuring sensor was presented in [95], and the results of the calibration indicated that the frequency response and linearity of the sensor were excellent. Experimental results also indicated that the sensor may record the time history of jerk motions.

An earthquake response monitoring technique for high-rise buildings by using a fibre optic jerk sensor was proposed in [96], and the results confirmed that the sensor can monitor jerk response of different seismic waves. Afterwards, the development of the fibre optic jerk measuring sensor was presented in [97], and a comparison of experimental and theoretical results was performed. It was stated that the application of the sensor has potential in earthquake engineering. A summary of the abovementioned works is reported in Table 4.

Table 4. Seismic jerk in sensors for structural health monitoring.

Field of Application	Reference	Motivation
Sensors and monitoring	Tsuchiya et al. [91,92]	Proposal of a mathematical model and a jerk sensor prototype
	Tamura et al. [93]	Discontinuities detection through a jerk sensor combined with a vibratory gyroscope
	Sone et al. [94]	Development of a sensor for the measurement of the time derivative of jerk (snap)
	Yang et al. [95]	Experimental results and calibration of a jerk-measuring sensor
	Wentao et al. [96]	Proposal of an earthquake response monitoring technique for high-rise buildings through a fibre optic jerk sensor
	Huicong et al. [97]	Development of a fibre optic jerk measuring sensor

6. Summary

A brief summary of the analysed jerk-related literature is provided in this section. Overall, there are 70 sources related to jerk applications in earthquake engineering. Their publication through the decades is summarized in Figure 5.

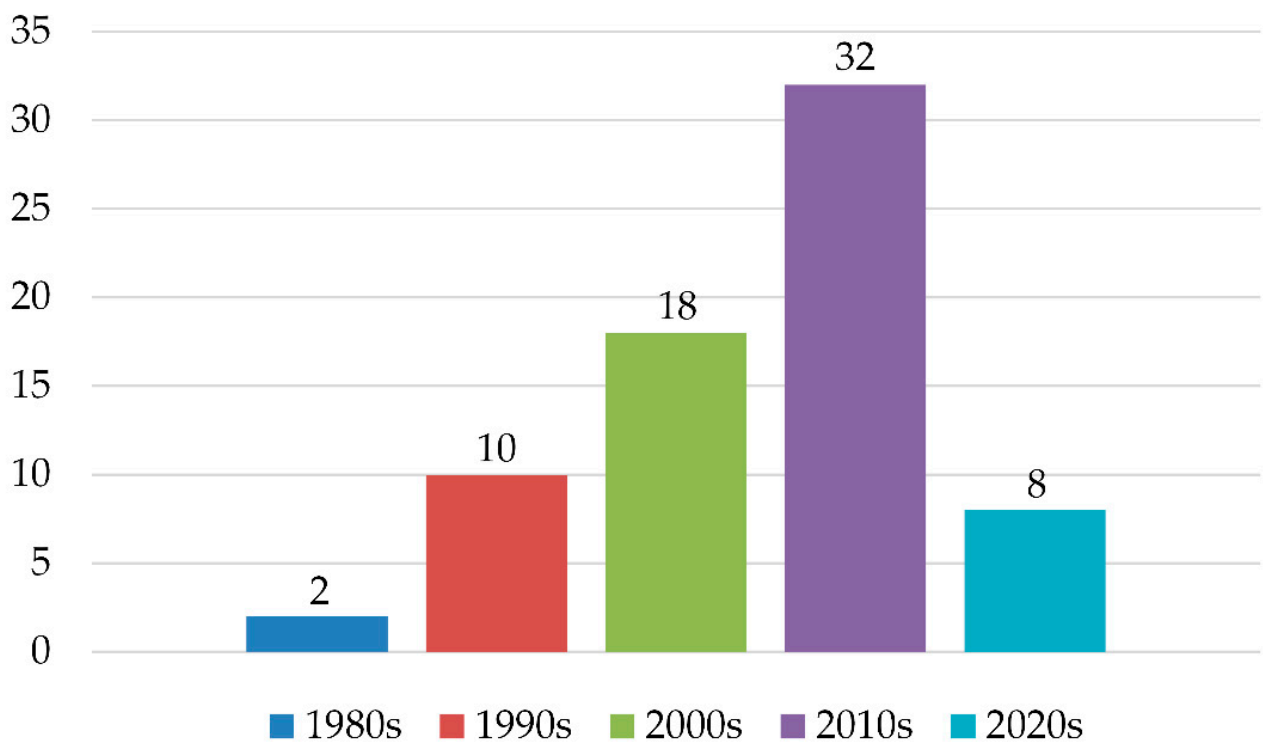

Figure 5. The publication of jerk-related sources through the decades.

Figure 5 confirms an obvious increase in the publication trend, with an almost doubled number of publications between the 1990s and 2000s, and 2000s and 2010s. Even though the current decade just started, eight papers were already published, indicating that the interest in jerk and its research will continue to increase in the following years.

Figure 6 shows a pie chart which summarises the applications of jerk in a way it was considered in this paper. It should be noted that, as stated in the Introduction, some sources cover more than one topic, so the contributions presented in Figure 6 are only an approximation, although it is clear that in more than half of the existing sources the considerations of jerk were related to structures and NSCs. The interest in jerk within the structural control, isolation systems, and dampers is similar as within the ground motions and acceleration data, whereas, when it comes to sensors and monitoring, it is the lowest with the contribution of about 10%.

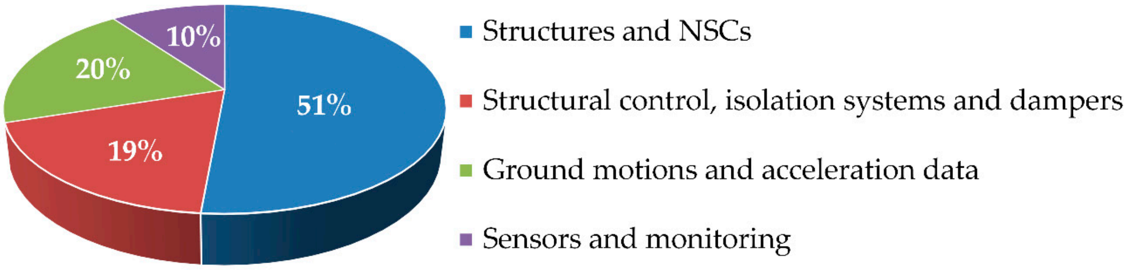

Figure 6. Summary of jerk applications in earthquake engineering.

7. Research Needs and Conclusions

The above literature overview shows that much progress has been made lately towards a better understanding of jerk, as well as its application in earthquake engineering. However, further research is needed in order to improve the states of the art and practice, which can be summarized as follows:

- It is of great interest to advance the understanding of the seismic response of structures in terms of jerk since some studies showed that damage is closely related to it. In addition, methodologies for jerk-based seismic analysis of structures are also needed, which would significantly improve the structural design aspects, both from theoretical and practical points of view.
- The above can be achieved through the analysis of jerk and acceleration data obtained from field measurements, testing, structural monitoring, and parametric numerical analyses, as well as from observations of structural damage. Thus, further development of jerk sensors and monitoring techniques should be performed.
- Jerk-related response of NSCs and equipment deserves further attention, particularly due to the fact that keeping in mind their high costs compared to structural parts, they have been a hot research topic in the last decade. A simplified methodology for jerk estimation on building floors is needed so that jerk-sensitive NSCs and equipment can be properly assessed.
- Consideration of jerk in seismic design codes is necessary, not only in terms of the response of structures, NSCs, and equipment, but also in terms of human (dis)comfort. Currently, no jerk-related data on the perception of humans exposed to earthquakes is available, and further research efforts are needed, as well as the acceptable jerk criteria definition.
- It is clear from the reviewed literature that structural control, isolation systems, and dampers can be successfully applied in the mitigation of jerk, implying that their further research and development are of interest.

Besides motion quantities such as displacement, velocity, and acceleration, which have been commonly used over the years, new frontiers need to be examined in order to improve future generations of seismic design codes, so that the built environment is in line with contemporary changes. Jerk represents a motion quantity for which it was shown that may have a great potential in earthquake engineering. It can be applied in various ways, but further research efforts are needed in improving existing usage and to discovering new possibilities for its application.

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