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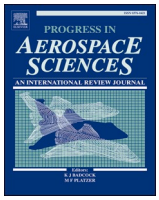



Progress in pyroshock simulation for qualification tests: A systematic literature review

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ABSTRACT

Spacecraft and their onboard equipment are subjected to significant dynamic loads, particularly when the activation of pyrotechnic devices induces intense high-frequency shocks, known as pyroshocks, which propagate throughout the entire structure and can cause critical damages. Qualification tests are needed to ensure aerospace equipment can withstand impulsive loads and therefore test rigs and simulation models are designed to replicate real-world pyroshocks while pursuing repeatability, accuracy, and safety.

This paper systematically categorizes and analyzes existing research papers on pyroshock simulation techniques, examining both experimental and numerical approaches. Scientific databases were queried but only a selection of the most relevant papers is presented and labeled, according the publication year, the purpose, the physical domain, the numerical method, the kind of fixture, and the excitation method. Additionally, a shorter review on contact mechanics is included to offer complementary insights, considering its relevance to pyroshock simulations.

1. Introduction

During their operational lifespan, space equipment experiences several loads, among which high-frequency shocks are notable [1]. Pyrotechnic devices, commonly employed in aerospace applications, utilize high-energy or explosive materials, originating the designation of pyroshock. These devices serve critical functions in executing mechanical tasks, enabling the initiation of flight sequences throughout various mission phases, including launch, orbit, and return.

Pyrotechnic devices function as essential components in tasks such as releasing spacecraft stages, boosters, cabins, satellites, and other structural subsystems. Their utilization offers numerous benefits, ensuring efficient operation, high reliability, and proper structural connections before separation. However, the activation of pyrotechnic devices initiates a transient mechanical response in nearby structural elements.

A shock, characterized by its brevity, high frequency, and significant amplitude, originates from the activation of pyrotechnic devices [2]. This shock propagates through tension-compression, flexural, or shear waves, involving intricate phenomena such as reflection, dissipation, and diffraction at boundary conditions or mechanical junctions. Waves reflect at boundaries and internal interfaces, generating a modal response within the system. Conversely, longer wavelength responses may propagate to various locations within the structure, even far from the shock origin [3].

Several factors characterize the nature of these acceleration transients: the typology of the pyrotechnic device, the geometry and properties of the structure, and the distance from the source [4]. Considering these characteristics, along with launch vehicle manufacturers' strategies to minimize spacecraft mass and costs by reducing damping materials, pyroshocks can induce deformations and structural damage. Electronic components and precision equipment, especially those realized with crystalline and ceramic materials, are particularly vulnerable to these shocks. As crucial elements for space missions, these materials exhibit high sensitivity both to shocks and high-frequency excitations [5].

Hence, it becomes necessary for space equipment to undergo shock tests for qualification, guaranteeing its ability to withstand propagated stresses. Furthermore, the rapid advancement in aerospace and defense technology, coupled with the continuous evolution of spacecraft, results in an increasing arrangement of pyrotechnic devices employed during missions. This highlights the importance of validation testing, making it an indispensable tool in the qualification process for aerospace equipment.

To address these needs, some technical standards, such as Method

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517 in MIL-STD-810F [6] and the IEST RP Pyroshock Testing Technique [7], provide guidelines for delineating these requirements. NASA-STD-7003 [8] classifies pyroshocks in three categories based on the distance between the source and the point of interest, each characterized by distinct spectral contents.

- *Near-field*: this category exhibits a significant spectral content exceeding 10 kHz in frequency and peak accelerations higher than 10^5 g. As a best practice, sensitive hardware should ideally be positioned at a considerable distance from potential shock regions during the design phase. Consequently, simulation test requirements primarily focus on the mid- and far-field categories.
- *Mid-field*: these shocks encompass frequencies ranging from 3 to 10 kHz, with accelerations typically of the magnitude order of 10^4 g. The mid-field content primarily arises from wave propagation and structural resonances.
- *Far-field*: this category involves frequencies below 3 kHz and peak accelerations lower than 10^3 g, primarily resulting from structural resonances.

Shocks are typically evaluated using time-domain acceleration signals. However, interpreting these time histories gives rise to challenges in quantifying, classifying, and comparing various impulses. Hence, the Shock Response Spectrum (SRS) [9] works as a prevalent tool for characterizing and comparing the frequency contents of pyroshock tests. Additionally, it outlines specifications for impact tests within the aerospace industry, although alternative methods have been proposed for component shock qualification [10]. In most cases, the maxi-max SRS is adopted, indicating the absolute maximum response in terms of acceleration. This is determined using a standardized set of mass-spring-damper systems, each with a Single Degree Of Freedom (SDOF), as qualitatively depicted in Fig. 1.

The aforementioned guidelines generally help in defining SRS requirements for pyroshock simulations with associated tolerance limits. These requirements are typically based on three critical frequencies: the minimum and maximum frequencies (around 100 Hz and 10 kHz, respectively) and the knee frequency (usually falling between 500 and 1500 Hz). Test specification curves often exhibit amplitudes characterized by a positive slope at low frequencies, followed by an approximately constant level at higher frequencies, as shown in Fig. 2. The amplitude values are determined based on the structural characteristics of the spacecraft and the nature of the explosions. The levels can vary for the same launch system depending on where the equipment is mounted in relation to the launcher itself. Additionally, there are further guidelines in the literature regarding the definition of tolerances, such as the experimental standard ESA ECSS [11]. Specifically, ECSS-E-ST-10-03C limits the SRS within a tolerance range spanning +6 dB to −3 dB relative to the nominal spectrum.

Pyroshock simulations are typically divided into two main categories: experimental and numerical. The choice between these approaches depends on several factors, including the type of pyroshock being investigated, equipment requirements, distance from the source, and structural configuration.

Experimental methods are commonly used to characterize and validate components subjected to pyroshocks. Traditionally, these methods involved the use of explosive charges. However, modern laboratory setups often employ bullets, pendula, or hammers in impact testing machines to improve repeatability and safety. Among the various excitation methods and structures, resonant plates are widely regarded as the most effective means of simulating pyroshocks. These plates allow test objects to experience responses similar to those generated by real pyroshocks. The shocks are induced by the impact of a typically metallic object on the resonant plate, so as to generate a spectrum that meets the specified test criteria.

Currently, the achievement of the desired test conditions in terms of SRS profile in pyroshock simulation techniques predominantly involves the definition of the experimental setup through empirical methods, often necessitating numerous trial-and-error iterations [12,13]. It is worth noting that the diverse experimental configurations utilizing resonant plates exhibit significant variations. Factors such as plate dimensions, materials, orientation, and boundary conditions, together with other parameters including the impacting body and the test object, contribute to this diversity. Introducing an anvil plate between the resonant plate and the impacting body may also modify impact characteristics and prevent plastic deformation of the resonant plate.

The challenges inherent in establishing qualification tests using trial-and-error methods are further complicated by the multitude of involved parameter combinations. Beyond these technical complexities associated with test tuning, test requirements may vary depending on spacecraft construction characteristics and the specific pyroshock attributes to be simulated. Mixing these factors introduces a substantial burden in terms of downtime and costs for preparing and fine-tuning the test facility. Therefore, some articles collected in this review propose the employment of numerical methods to accurately tune experimental tests, thereby reducing calibration times and enhancing precision.

While older studies on pyroshock trace back several decades, the development of this field is relatively recent, with a notable appreciation in scholarly attention over the past few years. A narrative review by Lee et al. [5] in 2012, focusing on the measurement and simulation of pyroshock, represents an early contribution. However, given the significant advancements in pyroshock research over the past decade, this work proposes a systematic literature analysis, which has not been presented before. The present study conducts a comprehensive literature review, systematically categorizing findings based on the experimental-numerical division. The combination of experimental and numerical techniques could be beneficial for a comprehensive understanding of pyroshock behavior on real components. Furthermore, considering the importance of impact physics in the context of pyroshock tests, an additional review is included to provide insights into contact mechanics, a topic that often progresses at the same pace as pyroshock simulation.

Building on these foundations, the primary objective of this review is to provide a comprehensive overview of current pyroshock simulation techniques, encompassing both experimental and numerical approaches. By synthesizing findings from the existing literature, this work aims to consolidate current knowledge into a coherent framework that

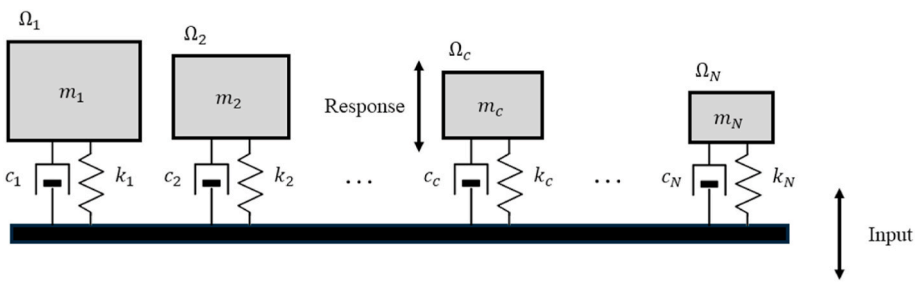

Fig. 1. Representation of the hypothetical series of independent SDOF mass-damper-spring systems defined for the SRS computation.

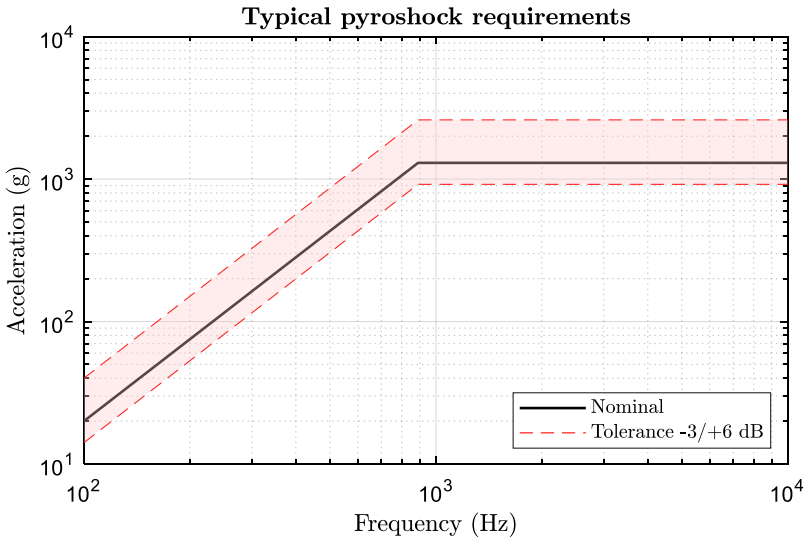

Fig. 2. Generic pyroshock requirement defined according to the standard guidelines.

enhances the understanding of pyroshock phenomena. This enables the identification of research gaps and methodological limitations to permit further advancements in the field, thereby laying the groundwork for future studies. Finally, this work aims to establish a solid foundation for future research and to guide the development of more accurate and standardized simulation practices in the context of aerospace applications.

The present paper is structured as follows. Section 2 briefly introduces the principles employed to identify and filter the papers present in the literature. Section 3 and 4 respectively describe the results and the discussion about the numerical and experimental methods. Section 5 introduces a narrative review to exhibit some interesting insights into the contact mechanics typically involved in pyroshock tests. Finally, Section 6 reports the conclusions.

2. Methodology and principles

The primary aim of this systematic literature review is to identify the predominant studies investigating experimental and numerical simulations of pyroshock within aerospace applications. Through the analysis of the selected articles, this paper aims to provide an overview of pyroshock tests, highlighting progress in this field and significant gaps in existing research. The essential criteria for filtering the articles can be summarized as follows.

- Subject related to pyroshock tests, also known as pyrotechnic shock tests;
- Application in the aerospace field for equipment qualification;
- Focus on techniques, methods, and simulation models, both experimental and numerical.

Moreover, the following further filters have been included.

- Year of publication between 1990 and 2024;
- Engineering as subject area;
- Only documents written in English.

For these reasons, an advanced search was performed on the Scopus database using the following search string:

((TITLE-ABS-KEY (“pyroshock test*” OR “shock test*” OR “shock response*” OR “shock environment*” OR “pyrotechnic”) AND TITLE-ABS-KEY (“space” OR “aerospace” OR “equipment” OR “qualification”) AND TITLE-ABS-KEY (“experiment*” OR “test*” OR “numerical” OR “model*” OR “technique*” OR “method*”) AND TITLE-ABS-KEY (“simulat*”)) OR (TITLE-ABS-KEY (“pyroshock” OR “pyrotechnic shock”))) AND PUBYEAR >1989 AND PUBYEAR <2025 AND (LIMIT-TO (SUBJAREA, “ENGI”)) AND (LIMIT-TO (LANGUAGE, “English”)).

Despite efforts to enhance the specificity of the search, the query conducted up until December 31, 2024 resulted in 495 outcomes. However, the search string was not made more stringent not to exclude pertinent articles related to pyroshock simulation. Therefore, the initial 495 articles underwent human selection, employing exclusion criteria. Specifically, studies were excluded if they were considered: (1) irrelevant in terms of the topic area, scope, application field, etc., (2) not significant, or (3) categorized as review documents. This manual filtering process led to the selection of 36 articles, summarized in Table 1. For each article, the main contribution was reported in terms of experimental or numerical methods. Additionally, relevant information about the studies was provided where available. Numerical methods were categorized based on domain (time or frequency) and numerical techniques (e.g., FEM, SEA, hybrid methods). Articles addressing experimental techniques or utilizing experimental data to validate numerical models were classified based on the type of the adopted resonant fixture (e.g., resonant plate, beam, bar) and the excitation source (pendulum/hammer, pneumatic gun, explosive charges, laser, etc.). A preliminary analysis suggests that almost 70 % of the articles were published within the last decade, indicating a growing interest in the subject. The trend is depicted in Fig. 3.

Since some studies were excluded from this search as they were not indexed (e.g., theses or company reports) or did not entirely meet search filters, 15 works considered relevant and interesting for the subject under investigation are additionally reported in Table 2.

To summarize the whole article selection process, Fig. 4 illustrates the flowchart leading to the final selection of the 36 articles identified in the database and the additional 15 works. The content of these 51 contributions is subsequently analyzed with a separate focus on experimental and numerical approaches.

3. Numerical simulation models

Numerical simulation uses mathematical methods to model the behavior of real systems. This approach is valuable for both simulating comprehensive pyroshock tests and predicting the response of experimental setups. Due to the current limitations in the analytical characterization of collision, which lacks sufficient detail to study structural behavior under impulsive loads, numerical models are essential. They

Table 1
Results of the literature review on the simulation of pyroshock tests for aerospace equipment qualification after the fine selection process.

Authors	Year	Aim	Physical Domain	Num.Method	ResonantFixture	ExcitationMethod
Abbas et al. [14]	2016	Exp.	–	–	Plate	MechanicalGun
Bae et al. [15]	2024	Exp.	–	–	Plate	Pendulum
Choi [16]	2013	Exp.	–	–	Plate	Laser
Dilhan et al. [17]	2005	Exp.	–	–	Plate	Explosive charges
Garcia-Perez et al. [18]	2020	Num.	Time	FEM	Plate	Pendulum
Gherlone et al. [19]	2004	Num.	Frequency	Hybrid	–	–
Houshmand et al. [20]	2015	Exp.	–	–	Plate	Electro-magnetic
Hwang et al. [21]	2016	Hybrid	Time	Hybrid	Plate	–
Iadevaia et al. [22]	2002	Num.	Time	SEA	Plate	Electro-dynamic
Iwasa et al. [23]	2008	Num.	Frequency	Hybrid	Plate	Hammer
Jeong et al. [24]	2017	Exp.	–	–	Bar + Plate	Pneumatic Gun
Kim et al. [25]	2022	Exp.	–	–	Plate	Pneumatic Gun
Kiryenko et al. [26]	2005	Num. + Exp.	Time	FEM	Plate	Pendulum
Lacher et al. [27]	2012	Semi-analytical	Time	–	Plate	Pendulum
Lee et al. [28]	2015	Exp.	–	–	Plate	Explosive charges + Laser
Li et al. [29]	2016	Num.	Time	FEM	Beam	–
Liu et al. [30]	2024	Num. + Exp.	Time	FEM	–	Explosive charges
Lu et al. [31]	2022	Exp.	–	–	–	Explosive charges + Piston
Mittal et al. [32]	2018	Num. + Exp.	Time	FEM	Plate	Pendulum
Monti et al. [33]	2017	Num.	Time	Hybrid	–	–
Morais et al. [34]	2016	Num. + Exp.	Time	FEM	Plate	Pendulum
Remedia et al. [35]	2017	Num.	Time	FEM	–	Shaker
Sadkin [36]	2004	Exp.	–	–	–	Shaker
Seefeldt et al. [37]	2018	Exp.	–	–	Plate	Nail gun
Soine [38]	2024	Exp.	–	–	Plate	Pneumatic Gun
Soine et al. [39]	2024	Exp.	–	–	Bar	Pneumatic Gun
Soine et al. [40]	2024	Exp.	–	–	Plate	Pneumatic Gun
Sutra et al. [41]	2005	Num. + Exp.	Time	FEM	Beam	Pendulum
Viale et al. [42]	2023	Num.	Frequency	FEM	Plate	Pendulum
Viale et al. [43]	2023	Num.	Frequency	FEM	Plate	Pneumatic Gun
Viale et al. [44]	2024	Num.	Frequency	FEM	–	–
Wang et al. [45]	2021	Num.	Hybrid	Hybrid	Plate	Pneumatic Gun
Wang et al. [46]	2022	Num. + Exp.	Frequency	SEA	Plate	Pneumatic Gun
Wattiaux et al. [47]	2008	Num.	Frequency	FEM	Plate	Pneumatic Actuator + Explosive charges
Yalcinkaya et al. [48]	2022	Num. + Exp.	Time	FEM	Plate	Pneumatic Gun
Zhao et al. [49]	2019	Exp.	–	–	Plate	Explosive charges

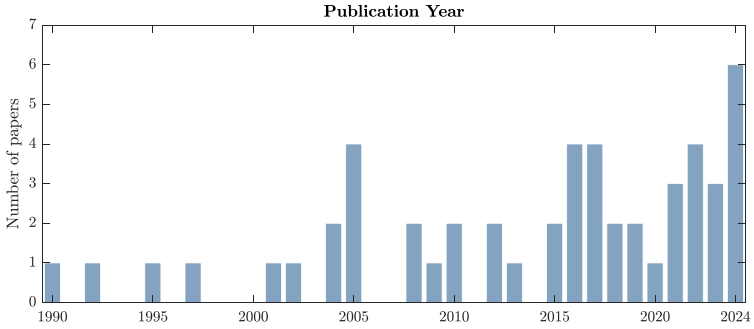

Fig. 3. Trend of publication years.

enable the analysis of impact test responses in the aerospace field, ensuring the verification of component resistance. The literature presents various approaches, often complex and involving multiple synergistic techniques. Generally, these approaches are classified into several macro-categories, with the Finite Element Method (FEM) and Statistical Energy Analysis (SEA) being the most prominent. These methods promote the analysis of wave propagation, thereby allowing the prediction and estimation of the dynamic response of mechanical systems.

The systematic literature analysis reveals that the majority of selected works utilize FE-based methods for the numerical simulation of pyroshock tests. Specifically, 17 out of 31 works (55 %) that include numerical methods propose an FE-based model. As illustrated in Fig. 5, the remaining works are distributed among SEA methods or hybrid models that integrate multiple approaches.

Additionally, most of these methods operate in the time domain, with 18 out of 31 studies using this approach. This correlation between the type of method and the domain is due to FEM typically employing transient analysis, a technique used to examine the dynamic response of a structure under time-varying excitations. Conversely, SEA methods generally operate in the frequency domain. A few selected studies employ Transient Statistical Energy Analysis (TSEA), which combines SEA with transient time-domain analysis. Notably, some studies use FEM to directly derive the Frequency Response Function (FRF) of the dynamic system.

Generally, FEM employs transient analyses in the time domain, which necessitate long computational times and generate substantial amounts of data. Conversely, SEA methods, operating in the frequency domain, have lower accuracy at low frequencies and cannot predict responses at specific frequencies or individual points due to their statistical nature. Numerical methods that combine the precision of FEM

Table 2
Relevant works included in the eligible contributions.

Authors	Year	Aim	Physical Domain	Num Method	Resonant Fixture	Excitation Method
Davie et al. [12]	1992	Exp.	–	–	Beam	Mechanical Sled
Davie et al. [13]	1997	Exp.	–	–	Bar	Mechanical Sled
Spletzer et al. [50]	2017	Exp.	–	–	Plate	Gas Gun
McGlaun et al. [51]	1990	Num.	Time	Hybrid	Block	Mechanical (Projectile)
Jonsson [52]	2012	Exp.	–	–	Plate	Pendulum
Cheng [53]	2021	Num.	Time	FEM	Beam + Plate	–
Kucukbayram [54]	2021	Num. + Exp.	Time	FEM	Plate	Hammer
Siam [55]	2010	Num. + Exp.	Time	FEM	Plate	Pendulum + Falling mass
Gomez [56]	2005	Num.	Hybrid	Hybrid	Plate	–
Dalton et al. [57]	1995	Num.	Frequency	SEA	–	–
Troclet et al. [58]	2009	Num.	Hybrid	Hybrid	Plate	–
Daga et al. [59]	2023	Num.	Frequency	FEM	Plate	–
Ullio et al. [60]	2001	Num.	Frequency	SEA	–	–
Lee et al. [61]	2010	Num.	Frequency	SEA	–	–
Liu et al. [62]	2019	Num. + Exp.	Time	Hybrid	–	Shaker

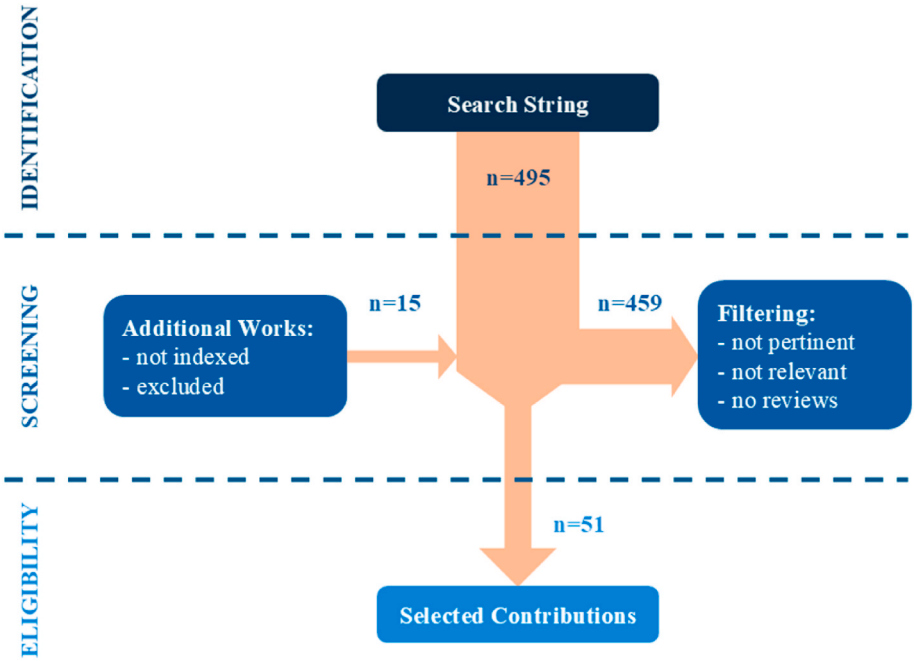

Fig. 4. Flowchart describing the selection process for systematic literature analysis.

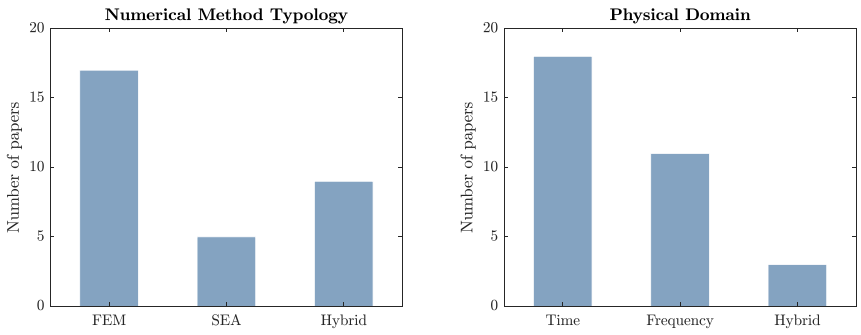

Fig. 5. Histograms inherent to the method typologies (on the left), and their domain (on the right) of the selected papers describing numerical methods for pyroshock simulation.

with the efficiency of frequency domain approaches offer accurate results without significantly increasing the computational burden.

3.1. Statistical Energy Analysis

The general approach known as Statistical Energy Analysis (SEA) is a methodology designed to address high-frequency vibroacoustic

problems. Given that pyroshocks exhibit high-frequency content, SEA has been effectively extended to predict pyroshock responses using steady-state power balance equations. Within SEA, the entire system under analysis is divided into a series of coupled subsystems, each representing a group of modes with similar characteristics.

This technique heavily relies on accurate estimation of input power, modal densities, damping loss factors, and coupling loss factors. The magnitude of the obtained average FRF using the SEA can be employed with Virtual Mode Synthesis and Simulation (VMSS) to predict transient responses. Many works, both old and recent, utilize the combination of these techniques, as in Refs. [46,57,61]. In the case of transient and shock loading, reference is made to Transient Statistical Energy Analysis (TSEA) [63,64]. Iadevaia et al. [22] proposed a TSEA procedure, applying SEA to study transient phenomena like the response of plate-like structures excited by shocks. SEA has gained significant attention in research focused on predicting high-frequency structural responses. Compared to FEM, SEA is considered more suitable for high-frequency dynamic problems, as it is simpler to apply and often produces more accurate predictions at lower computational costs. Ullio et al. in Ref. [60] suggest to use SEA in favor of or in combination with FEM. However, it is crucial to understand that SEA is restricted to high-frequency applications and yields average responses across spatial regions and frequency bands, rather than specific points or frequencies. The fundamental SEA equations incorporate principles from statistical mechanics, acoustics, wave propagation, and modal analysis. This integration makes the process of choosing subsystems and evaluating parameters both complex and challenging.

3.2. Finite Element Method

The Finite Element Method (FEM) is a fundamental technique used to model, simulate, and predict shock responses in both time and frequency domains. As a deterministic method, FEM requires detailed knowledge of all structural parameters. The process involves discretizing complex structures into smaller elements and then solving a series of differential equations that describe their behavior. FEM is particularly effective for accurately simulating a structure's response to static and dynamic loads at mid and low frequencies. In the context of pyroshocks, FEM enables the application of well-characterized shock and vibration excitations to predict structural responses. It allows for precise calculation of structural and acoustic modes over a wide frequency range, making it suitable for analyzing complex dynamic systems. For these reasons, Finite Element Analysis (FEA) is one of the most used methods nowadays in the industrial field for static and dynamic structural analyses. Yalçinkaya et al. [48] demonstrate the potential of an explicit finite element solver for predicting experimental SRS curves. Remedia et al. [35] propose virtual testing modeled through FE. Perez et al. [18] introduce FEM transient analysis to verify the structural design of a Supra Thermal Electrons and Protons (STEP) unit. The same authors in Ref. [65] provide an overview of the numerical analyses that can be used for shock test qualification by exploiting the FEM. They demonstrate that FEM can be adequate for analyzing small structures subject to shock loads, as the need for a sufficiently fine mesh is not a critical issue, and simultaneously, it is possible to obtain appropriate accuracy for the simulations. In this study, an overview of analysis options using FEM to simulate shock loads is provided. The methodologies include.

- *Transient analysis* is the most general and calculates the behavior of a structure subjected to time-varying loads. It offers the advantage of obtaining temporal functions for various outputs but requires high computation times and produces a large amount of data.
- *Response spectrum analysis* estimates peak responses using modal analysis of the structure, but it has limited precision.
- Sine *transmissibility method* calculates SRS curves of the response acceleration by multiplying the input SRS by the shock transmissibility. However, it cannot determine peak values or time domain functions.
- *Equivalent quasi-static load method* provides an approximation of the total interface force of the shock load.

Other studies have developed numerical simulation models in the frequency domain [43,44,59] and integrated FEM parametric model with a Genetic Algorithm (GA) optimizer [42] to simulate pyroshock tests and optimize test facility designs for spacecraft equipment. This innovative approach offers enhanced accuracy, flexibility, and cost-efficiency in qualification testing.

However, FEM has several limitations. When dealing with high modal densities, FEM becomes computationally expensive, involving limits in mesh size and allowing accurate modeling only for relatively simple structural configurations. Despite these constraints, simulations on simplified models generate SRS predictions consistent with measured tests at low frequencies. Studies have demonstrated that FEM methods for simulating pyroshock responses are valid for simplified systems such as beams and plates, as shown in Refs. [34,53]. It is worth emphasizing that, despite its versatility, FEM may be less suitable for simulating pyroshock tests characterized by significant nonlinearities and high frequencies.

3.3. Other methods

Nonetheless, the integration of FEM, a deterministic method, with SEA, a statistical method, into a single model is challenging due to their fundamentally different principles. Researchers have proposed hybrid models for mid-frequency simulations to address the limitations of FEM and SEA at high and low frequencies, respectively. Mid-frequency systems can be too complex for FEM and not sufficiently random for SEA. In a hybrid model, the system response is divided into subsystems managed by either FEM or SEA based on modal density, providing a more effective approach for medium frequencies. Troclet et al. [58] developed a method combining FEM and SEA to predict responses at mid and high frequencies. Similarly, Wang et al. [46] applied a hybrid approach, but their method showed significant errors when compared to experimental results.

Some methods are classified under the category of hydrocodes, which are computational techniques based on differential equations for modeling unstable dynamic motion. Hydrocodes are used to simulate pyroshock through coupled or decoupled approaches, performing either comprehensive or separate analyses of the initiation-explosion and structural response. This temporal method effectively simulates the dynamic response to typical pyroshock events. By integrating complex material models with structural fluid dynamics, hydrocodes are accurate in highly dynamic scenarios, particularly involving shock waves. However, while efficient for simple structures, hydrocodes become resource-intensive and require extended computation times for complex structures, making them powerful but demanding with limited predictive accuracy.

4. Pyroshock experimental techniques

The experimental simulation of pyroshock tests aims to replicate the propagation of shock waves as generated by the real system. These simulations can be classified into three main categories: (1) exciters using explosive charges or pyrotechnics, (2) mechanical exciters, and (3) optical exciters. Mechanical exciters include a diverse range of impact generators, such as pendula, hammers, pneumatic guns, and nail guns. The use of lasers to simulate shock wave propagation is a less established and less common methodology in literature. A systematic review of selected studies reveals that the majority of test benches (69 %) utilize mechanical exciters, while only a few studies describe the use of pyrotechnic or laser excitation systems. Fig. 6 illustrates that a significant number of other excitation types are used, with electrodynamic

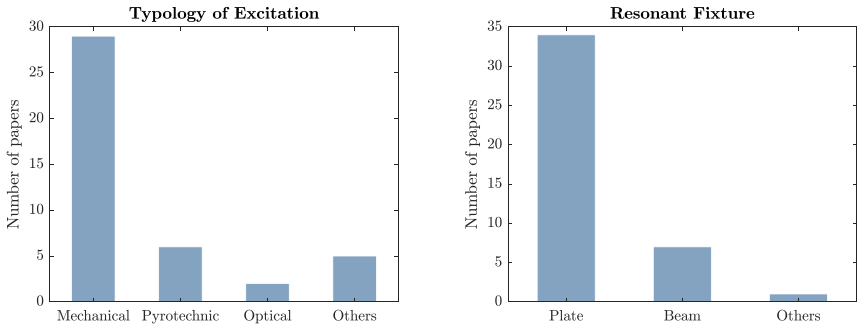

Fig. 6. Histograms inherent to the excitation techniques (on the left), and the adopted resonant fixtures (on the right) of the selected papers describing experimental test benches for pyroshock simulation.

excitations via shakers being predominant.

A systematic literature analysis reveals that resonant plates are the most widely used fixtures for simulating pyroshock tests. After generating an impact using various techniques, an interposed element, such as a resonant plate, is necessary for proper calibration of the test bench and for transmitting the shock wave to the component under test. Resonant plates are the most well-known and commonly used method in pyroshock simulations. However, it is noteworthy that some studies (17 %) utilize beams and bars as alternatives to resonant plates.

Some experimental setups described and illustrated in the literature demonstrate the effectiveness and performance of using interchangeable resonant plates, which are the most prevalent method due to their widespread use. This is also true for mechanical excitation techniques, where the pneumatic gun and pendulum are considered the most efficient, accurate, and repeatable. These two systems generate different impulses with the same momentum: the pneumatic gun launches projectiles with lower masses at high speeds, while the pendulum uses impacting bodies with higher masses but has a limit on the maximum achievable speed.

4.1. Resonant fixtures

Resonant fixtures are the most widely adopted technique for the experimental simulation of pyroshock due to their ability to reduce trial-and-error iterations in testing. These fixtures are designed with a fixed knee frequency (see Fig. 2) that calibrates their dominant resonant frequency with the SRS knee frequency. Adapters are used to connect the test object and simplify acceleration measurements on all three axes. Resonant fixtures provide good tuning and repeatability of the SRS, although the test object can influence their frequency content. Fig. 7 sketches various types of resonant fixtures used in the pyroshock tests.

The resonant plate is the most frequently utilized fixture for simulating pyroshock tests. The test object is mounted onto the metallic resonant plate, which can either be suspended to replicate free-free boundary conditions or fixed to the support structure of the test bench. Mechanical impact, typically applied to an interposed anvil plate, induces vibrations in the resonant plate. Modifications to the plate configuration can adjust resonance frequencies, allowing for tuning the experimental setup to meet different requirements. Calibration adjustments primarily involve variations in impact position, utilization of interposed anvil plates, damping via polymeric layers, and alterations in the arrangement of the test object. Recently, a few studies, such as [40], have focused on advancing mechanical shock testing by investigating novel resonant plate configurations to improve the shock responses across multiple axes within a single test event.

Experimental setups utilizing bars or beams work as alternatives to the resonant plate. The primary distinction between these resonant fixtures lies the wave propagation mechanism: bars transmit longitudinal waves, while beams exploit flexural modes. In configurations with a resonant bar, the test object is fixed at one end, and mechanical impact is applied at the opposite extremity, inducing resonance in the bar's longitudinal modes. These modes can be adjusted by adding weights at specific positions along the bar. Conversely, the resonant beam is fixed to a massive base to simulate a cantilever beam. Mechanical impacts are applied to excite its flexural modes. Davie et al. have proposed two adjustable configurations for pyroshock simulation in Refs. [12,13], utilizing a beam and a bar as resonant fixtures, respectively.

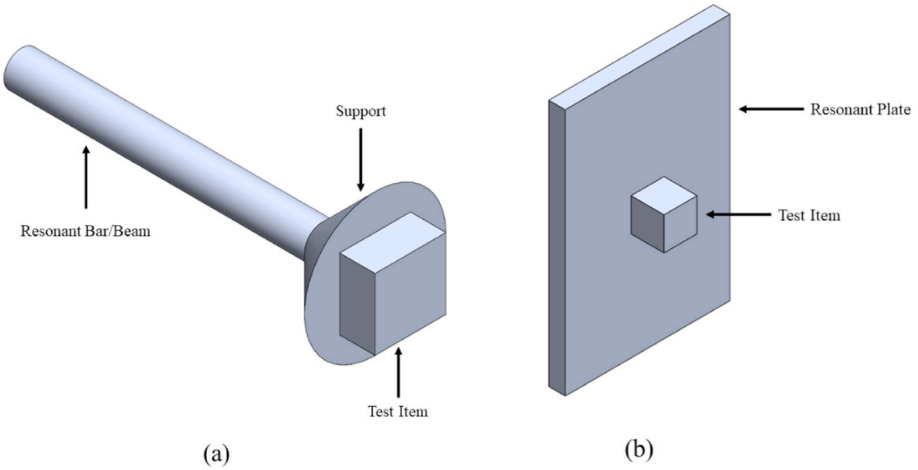

Fig. 7. Different typologies of resonant fixtures: (a) resonant bar/beam, and (b) resonant plate.

4.2. Mechanical excitation

A variety of simulation methods are employed for mid- and far-field shocks using mechanical excitations. These methods include dropping masses, pendulums, hammers, actuators, and projectiles launched by gas guns, nail guns, or sleds. Each method offers distinct advantages, and the selection depends on the precise test requirements, specifications, and characteristics of the test object.

In test benches exploiting falling masses, the impact is produced by dropping a table onto the test object through an appropriate device and spring connections, as illustrated in Fig. 8. However, this type of test bench is considered the least suitable for simulating pyroshock because the resulting impacts generate a transient response that significantly differs from the real behavior of explosive charges. Drop tables can induce severe overtesting at low frequencies, leading to structural failures that would not occur with real pyroshocks. The limited effectiveness of this test bench is underscored by the scarcity of studies in the literature that utilize drop tables.

Test benches employing pendulums or hammers to generate shock waves are more common. A representative illustration of these setups can be seen in Fig. 9. This technique involves a pendulum with mass m released from a height h to hit the resonant fixture. The shock magnitude, duration, and frequency range depend on several factors, including the geometry and material of the impacting bodies, the pendulum's mass and velocity, and the positions of both the impact and the test object. This method generates repeatable results and produces high momentum. However, the main limitation is the maximum speed achievable for the impact, which is reachable at the pendulum's lowest point in its trajectory and is directly proportional to the initial height, as determined by the formula $v_{MAX} = \sqrt{2gh}$. When impacting a resonant plate, the pendulum can be configured in two main ways based on the direction of the impact: Out-Of-Plane (OOP) and In-Plane (IP) configurations. In the OOP configuration, the impact is applied perpendicular to the resonant plate, primarily exciting its flexural modes. On the contrary, in the IP configuration, the impact is applied parallel to the plate plane. Morais et al. [34] propose an experimental setup that utilizes the response of a resonant plate excited by a pendulum in the IP configuration to simulate a shock environment. Similar proposals are made by Jonsson [52], Mittal et al. [32], and Kiryenko et al. [26], although they consider both IP and OOP configurations.

Equally common are projectile launchers, which typically use pneumatic systems to shoot a projectile against the resonant fixture. In some specific cases, the projectile is replaced by a piston or an actuator. Unlike pendula, pneumatic guns can achieve high-velocity impacts, though they are limited by the mass of the impacting bodies. The velocity and mass of the colliding body allow for generating different impacts, thereby tuning the test bench to meet various frequency content requirements. Notable studies in the literature proposing pneumatic gun-based test benches for simulating pyroshock include those by Yalçinkaya et al. [48], Wang et al. [46], and Jeong et al. [24]. A particularly innovative approach is presented by Kim et al. [25], suggesting a resonant device interposed between the plate and the pneumatic gun.

4.3. Pyrotechnic excitation

Explosive charges are employed to evaluate structural integrity and design functions by generating high accelerations and frequencies. Pyroshock is induced by detonating charges on a resonant plate. This setup often requires numerous trial-and-error iterations, making the process costly and time-intensive. A dummy object is typically used during the calibration phase. Beyond the time and costs, this method leads to several critical issues: the inherent risks of handling and detonating explosive charges, and the potential damage to the structure during each test. Therefore, a specially qualified structure and strict safety procedures are necessary for handling explosives. Additionally, the use of real explosive charges can give rise to significant variability in impacts, thereby reducing the repeatability of shock spectra compared to mechanical exciters. Fig. 10 illustrates an example of a test bench designed to simulate pyroshock effects using explosive charges.

Dilhan et al. [17] proposed a characterization of eleven different typologies of pyrotechnic devices with various operating principles, materials, and amounts of explosive charge. Zhao et al. [49] suggest a test bench configuration to generate excitation through an explosive charge appropriately positioned in a protective cover with a suitable exhaust hole to allow gas release.

4.4. Other techniques

In addition to the widely used mechanical and explosive excitations, optical and electrodynamic techniques are sometimes employed, such as laser and shaker excitations.

Laser excitation involves using an optical pulse to generate transient

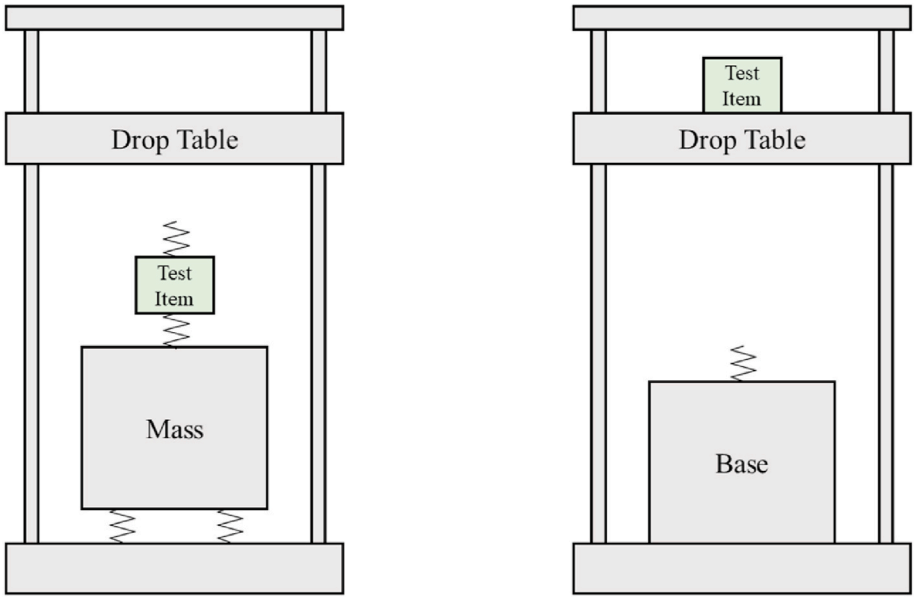

Fig. 8. Examples of drop tables for pyroshock testing.

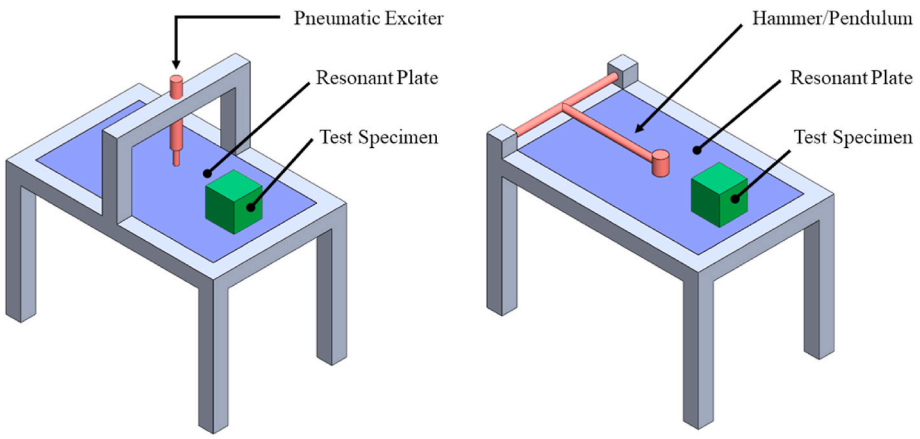

Fig. 9. Examples of pyroshock simulator exploiting mechanical excitation techniques: on the left, pneumatic exciter, and, on the right, hammer or pendulum.

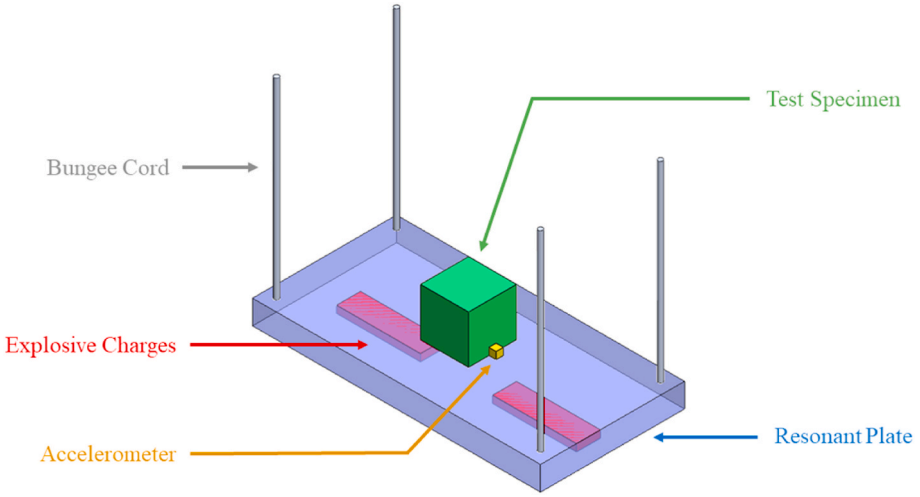

Fig. 10. Qualitative representation of a pyroshock simulator through explosive charges.

localized heating near the material surface, which produces thermoelastic stresses and deformations acting as a wave source. However, its main limitation is its inability to achieve high-magnitude excitations. An experimental simulation of pyroshock using laser excitation is presented by Choi in Ref. [16], where a Q-switched Nd:YAG diode-pumped solid-state laser was used. An alternative setup employing laser-induced shock is described by Lee et al. [28].

Transient responses to pyroshock can also be simulated using electrodynamic shakers. The main limitations of this technique involve restricted frequency ranges and maximum achievable accelerations. Despite the high precision typically associated with shakers, they are generally suitable only for simulating low-energy pyroshock events. For instance, Liu et al. [62] validated the effectiveness of their approach by conducting experimental pyroshock simulations with shakers. Additionally, Remedia et al. [35] utilized the Hydra shaker, which can generate excitations along all six degrees of freedom. To address the bandwidth limitations inherent to shakers, Houshmand et al. [20] proposed an alternative experimental setup. Their method involves using an electronic pulse generator and a coil to produce a magnetic field, which in turn induces currents on the plate, thereby propagating the wave.

5. Contact mechanics insights

The domain of contact mechanics is so extensive that a comprehensive literature review would still fall short of providing an exhaustive exploration. Unlike the systematic review of pyroshock simulation methods, this section does not aim to cover the entire state of the art in contact mechanics. Instead, it offers an overview of fundamental concepts that are particularly relevant to those interested in pyroshock testing. The focus is on various contact dynamics approaches, starting with models that describe perfectly elastic contacts based on Hertzian contact theory, then moving on to non-Hertzian viscoelastic and elastoplastic models. Finally, the discussion includes the coefficient of restitution, which is frequently used in contact mechanics to quantify the energy lost during an impact.

In general, multiple approaches can be employed to describe contact mechanics. The primary category consists of elastoplastic static contact models, which segment the contact process into three distinct phases: elastic, elastoplastic, and fully plastic. The elastic phase is typically analyzed using Hertzian contact theory. However, when the contact deformation surpasses a critical threshold, the deformation is no longer purely elastic, and Hertz's theory becomes inadequate. The onset of plastic deformation is analytically defined using a specific yielding criterion. Subsequently, the fully plastic phase can be modeled by theories such as von Mises yield criterion.

A second significant category of contact mechanics approaches uses continuous contact models, which account for energy dissipation through hysteresis cycles. These models operate on the principle that interaction forces persist throughout the impact. The foundational theory remains Hertzian, describing contact between perfectly elastic bodies without considering energy dissipation. To address this limitation, various models have been developed over the years. Notable

among these are the Kelvin-Voigt and Hunt-Crossley models. The Kelvin-Voigt model employs a linear spring-damper system that incorporates energy dissipation during contact via the damping term. Hunt and Crossley enhanced the Kelvin-Voigt model by introducing a damping coefficient dependent on contact deformation.

Lastly, certain approaches simplify contact dynamics by assuming rapid interaction between bodies, neglecting variations in their configuration during impact. These approaches divide contact dynamics into two main phases: before and after impact. Here, energy dissipation is characterized by coefficients, such as the coefficient of restitution.

5.1. Hertzian contact theory

The Hertzian contact theory represents a fundamental contribution to understand elastic deformation and contact mechanics between solid bodies. The theory deals with interactions that occur when two elastic spheres come into contact under quasi-static normal force. Hertz's model provides crucial insights into stress and deformation distribution at the contact interface, establishing a mathematical framework to analyze and predict material behavior under compression. Specifically, Hertz's theory focuses on determining the dimensions and contour of the contact area, along with the distribution of pressures and deformations within this area. The theory assumes that the materials involved are linearly elastic, isotropic, and homogeneous, and that deformations are sufficiently small to maintain elastic behavior.

The foundational texts on elasticity theory include comprehensive works by Love [66] and Landau-Lifshitz [67], renowned for their mathematical rigor. Leroy [68] has provided a qualitative approach to complement these mathematical treatments. Expanding on Hertzian theory, Gugan [69] extends its applicability to include contact between a sphere and a flat surface. This study demonstrates that Hertzian theory accurately models even inelastic contacts where up to 40 % of kinetic energy is dissipated during collision. The author attributes this accuracy to the theory's ability to effectively estimate contact area and duration during the compression phase, which aligns well with the predictions of elastic theory despite significant energy loss.

5.2. Viscoelastic and elastoplastic models

Viscoelastic and elastoplastic theories represent advancements in contact mechanics that address the limitations of Hertzian theory, particularly in terms of energy dissipation and material plasticity. Unlike Hertzian theory, which assumes purely elastic behavior, elastoplastic contact theories account for situations where materials undergo both elastic and plastic deformations upon contact. In elastoplastic contact, solid bodies experience irreversible deformations, providing a more realistic depiction of material behavior under contact conditions, especially when applied loads exceed the elastic limits of the involved materials. Fig. 11 illustrates various contact mechanics models characterized by their force-indentation curves.

In the field of impact physics, numerous viscoelastic and elastoplastic models have been developed, with several scholars offering comprehensive reviews of the field's advancements. Ghaednia et al. [70], for instance, categorize models for describing single asperity elastoplastic contacts based on the geometry of the impacting bodies. They classify models into three main groups: flattening models, which treat the flat surface as rigid with deformations concentrated on the sphere; indentation models, which consider the sphere as stiff and the plate as deformable; and comprehensive models that generalize impacts by accounting for both deformable bodies. Additionally, Kerr [71] and Younesian et al. [72] have contributed reviews on elastic and viscoelastic models used in foundation mechanics. While foundation models traditionally describe static contacts in structural mechanics, their adaptation to impact mechanics showcases a progression toward incorporating viscoelastic and nonlinear material effects over time. This evolution underscores ongoing efforts to refine models for more accurate representations of real-world impact scenarios.

The earliest model, introduced by Winkler [73], is a simple linear elastic model where the foundation is represented as a series of independent linear springs. These springs linearly relate pressure and deformation according to a material-specific elastic constant k. Filonenko-Borodich [74] advanced this model by adding an elastic membrane to enable interaction between the elastic elements, while Hetényi [75] assumed that the beam or plate deforms only through bending. Pasternak [76] further refined the model by incorporating shear interactions between the elastic elements. To address the limitation of purely elastic behavior, researchers extended Winkler's foundation model by integrating a viscoelastic element, as seen in the Kelvin-Voigt model [77], which represents the foundation as a series of parallel spring-damper systems. An alternative approach is the Maxwell model [77], where dampers are arranged in series with the springs. These foundation models have numerous variations, differing in the number of springs and dampers, their configuration (series or parallel), and the number of layers in the model. Despite its advancements, the Kelvin-Voigt model has drawbacks, particularly in the hysteresis cycle, which appears as a semi-ellipse with a discontinuity at the origin. This discontinuity introduces an unrealistic traction force during the separation phase of the impacting body. To resolve this, Hunt and Crossley [78] proposed a viscoelastic contact model with a damping coefficient dependent on contact deformation, resulting in a closed hysteresis cycle that converges at the origin. These foundation models are illustrated in Fig. 12.

5.3. Coefficient of restitution

Impact, defined as the collision between two bodies in a short time

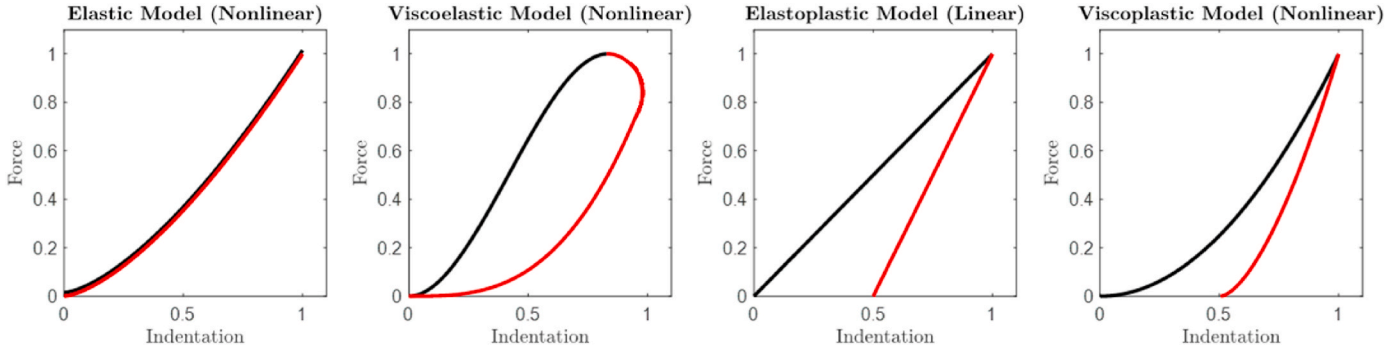

Fig. 11. Example of contact mechanics models classified by the force-indentation curve. The black and red curves respectively represent the compression and restitution phases composing the hysteresis cycle. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

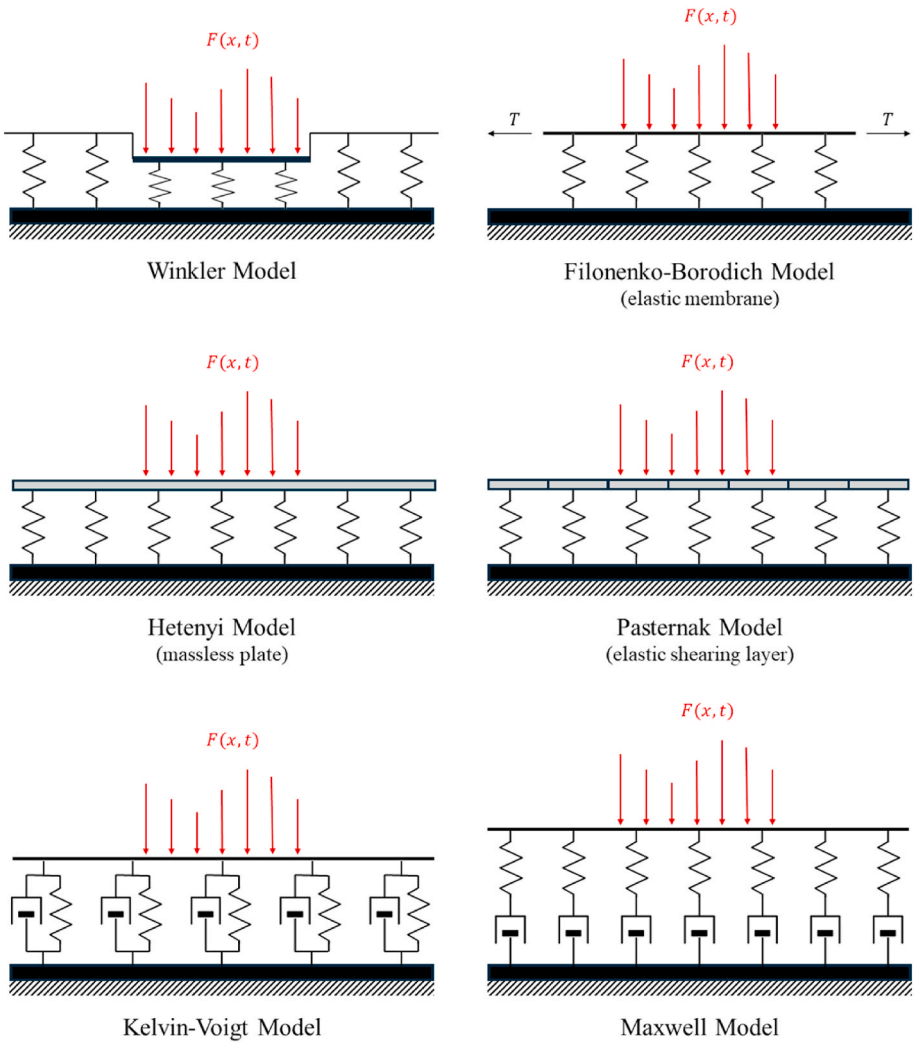

Fig. 12. Schematic representation of the main foundation models.

frame, is a highly complex physical phenomenon. Continuous impact models can be very intricate and depend on numerous parameters. To simplify impact modeling, studies have introduced the Coefficient Of Restitution (COR). The development of these models aims to derive the behavior of bodies in the post-impact phase based on the known behavior in the pre-impact phase. Due to the high forces experienced over very short durations during an impact, the event can be divided into two distinct phases. The first phase, known as the compression phase, spans from the initial contact of the bodies until their maximum compression. The second phase, called the restitution phase, begins when the bodies start to separate and ends when they are fully detached.

In this context, the COR quantifies energy loss during an impact. The COR ranges from 0 to 1, where 0 signifies a completely plastic collision with full energy dissipation, and 1 denotes a perfectly elastic collision with total energy conservation. The COR depends on various factors, including the geometry of the bodies, initial velocity, material properties, and contact duration. During an impact, the initial kinetic energy is partially lost through material damping, plastic deformations, wave propagation, and conversion to thermal and acoustic energy. Although the COR can theoretically exceed 1 if additional energy is introduced, such as from a chemical reaction during the collision, values greater than 1 are rare and typically indicate specific, exceptional circumstances.

Newton was the pioneer in studying the impact between two rigid bodies. He defined the COR as a kinematic quantity that relates the perpendicular velocities before and after the impact at the contact point. According to this model, the COR (typically denoted by the letter e) is calculated using the following formula:

$$e = -\frac{u_f}{u_i} \tag{1}$$

where u_f and u_i are the relative post-impact and pre-impact velocities respectively. Subsequently, Poisson's model proposed a similar concept, defining the COR as a kinetic quantity that correlates the perpendicular impulses during the compression and restitution phases:

$$e = \frac{\Delta p_r}{\Delta p_c} \tag{2}$$

where $\Delta p_r = \int F_r \, dt$ and $\Delta p_c = \int F_c \, dt$ are the normal impulse for restitution and compression respectively. Nevertheless, Stronge [79] identified energetic discrepancies in specific cases analyzed by using Poisson model. To solve this issue, Stronge suggested defining the COR as the square root of the ratio between the energy released during restitution and the energy absorbed by deformation during compression:

$$e = \sqrt{-\frac{W_r}{W_c}} \tag{3}$$

where W_r and W_c are the energy released during the restitution and compression phases, respectively.

In literature, many studies propose the COR estimation by considering variations in impact configuration, such as changes in the geometries of impacting bodies, impact velocities, and material properties. Notable contributions in this area include the works of Zener [80] and Weir-Tallon [81], which are particularly relevant and well-regarded in the field.

6. Conclusions

This work proposed a systematic analysis of the literature regarding pyroshock tests. The definition of impulsive phenomena and the classification of shocks is introduced to the reader, together with the concept of SRS, the most common representation to describe the frequency contents of shocks. Beyond providing an overview of pyroshock tests, a state-of-the-art is proposed to survey the scientific literature, with a particular focus on studies related to simulation models and experimental setups.

The results indicate that combining a mechanical exciter, such as a pneumatic gun or a pendulum, with a plate as a resonant fixture is an effective approach for experimentally simulating pyroshocks. This experimental setup is predominantly used in the test rigs described in the literature. For the numerical prediction of pyroshock tests, there is no widely adopted solution. The studies are mainly divided into FE-based and SEA-based models, each with its own advantages and disadvantages. FEM models, typically developed in the time domain, offer high precision at medium-low frequencies, but require long computation times. Conversely, SEA models can reach higher frequencies but with reduced accuracy in the low frequency band. A potential compromise could be achieved through hybrid methodologies, such as combining FEM and SEA models or implementing FEM models developed in the frequency domain.

Despite the progress made in the field of pyroshock testing and simulation, the findings from this systematic literature review reveal that several significant limitations persist in both experimental and numerical methodologies. Experimentally, there is currently no homogeneous or widely accepted test setup for pyroshock qualification, leading to inconsistencies in results and difficulties in benchmarking across different studies. Furthermore, the absence of standardized procedures and reference methodologies limits both reproducibility and broader applicability. Numerical simulation approaches, although increasingly advanced, still lack a high-precision and comprehensive methodology capable of reliably predicting pyroshock responses across the entire frequency spectrum. Errors in SRS predictions remain a critical issue, particularly in the high-frequency range. As a result, pyroshock qualification tests for components remain costly and time-consuming, often leading to overtesting due to the current level of uncertainty.

To address these challenges, future research should focus on the development of more robust simulation frameworks and standardized experimental protocols. In particular, the advancement of digital twin technologies holds significant promise, offering the ability to virtually replicate test environments with high fidelity and substantially reduce downtime and cost. Moreover, the implementation of standardized testing procedures and common experimental setups would promote the generation and collection of high-quality datasets. These datasets could in turn support deeper investigation into pyroshock behavior and enable the development of data-driven approaches – including the application of artificial intelligence algorithms – to enhance simulation accuracy. Such innovations, combined with greater methodological harmonization, will be essential in closing the gap between current practices and the need for reliable, efficient, and scalable pyroshock simulation solutions.

Finally, a narrative overview of the state of the art in contact mechanics is presented to provide additional insights, given its importance in the context of pyroshock simulations. Contact mechanics is important in accurately modeling interactions between components during shock events, which involve high-frequency vibrations and impacts. Understanding these interactions may improve the precision of simulation results and ensure that predictions more closely reflect real-world behavior.

CRediT authorship contribution statement

Luca Viale: Writing – review & editing, Writing – original draft, Visualization, Validation, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Alessandro Fasana:** Writing – review & editing, Validation, Supervision, Resources, Project administration, Investigation, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

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