POLITECNICO DI TORINO
Repository ISTITUZIONALE

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

*Original*
Progress in pyroshock simulation for qualification tests: A systematic literature review / Viale, L., Fasana, A.. - In: PROGRESS IN AEROSPACE SCIENCES. - ISSN 0376-0421. - ELETTRONICO. - 157:(2025), pp. 1-13. [10.1016/j.paerosci.2025.101126]

*Availability:*
This version is available at: 11583/3001109 since: 2025-06-19T08:21:26Z

*Publisher:*
Elsevier

*Published*
DOI:10.1016/j.paerosci.2025.101126

*Terms of use:*

This article is made available under terms and conditions as specified in the corresponding bibliographic description in the repository

*Publisher copyright*

(Article begins on next page)

01 November 2026

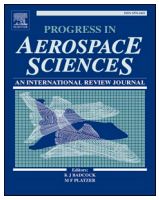
Progress in Aerospace Sciences 157 (2025) 101126



Contents lists available at ScienceDirect

Progress in Aerospace Sciences

journal homepage: www.elsevier.com/locate/paerosci





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

Luca Viale, Alessandro Fasana *

*Department of Mechanical and Aerospace Engineering, Politecnico di Torino, Corso Duca degli Abruzzi 24, 10129, Torino, Italy*

ARTICLE INFO

*Keywords:*
Pyroshock
Numerical methods
Experimental techniques
Contact mechanics
Aerospace equipment qualification

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

* Corresponding author.
*E-mail address:* alessandro.fasana@polito.it (A. Fasana).

https://doi.org/10.1016/j.paerosci.2025.101126
Received 7 March 2025; Received in revised form 9 June 2025; Accepted 10 June 2025
Available online 15 June 2025
0376-0421/© 2025 The Authors. Published by Elsevier Ltd. This is an open access article under the CC BY-NC-ND license (http://creativecommons.org/licenses/by-nc-nd/4.0/).

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

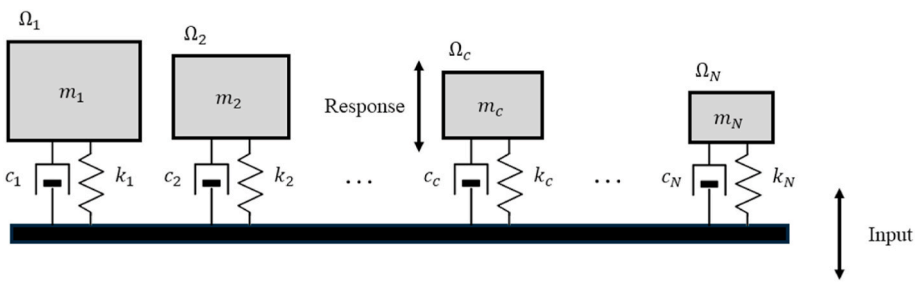



**Fig. 1.** Representation of the hypothetical series of independent SDOF mass-damper-spring systems defined for the SRS computation.

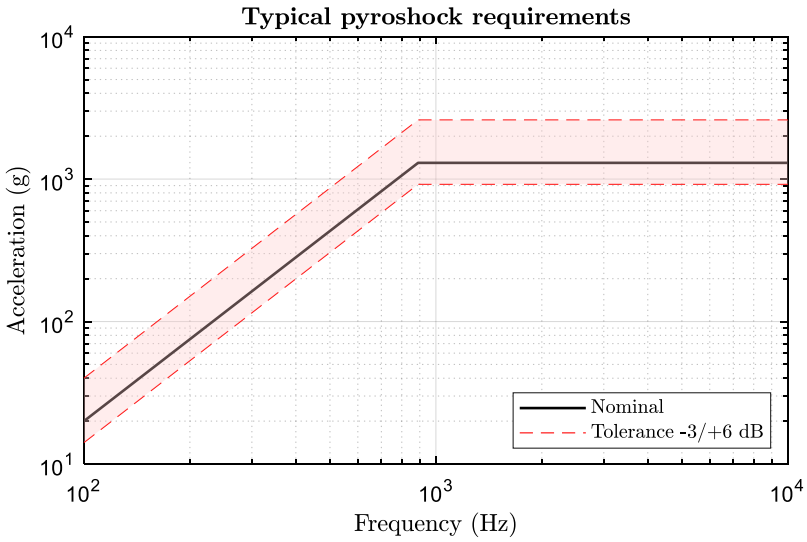



**Fig. 2.** Generic pyroshock requirement defined according to the standard guidelines.

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 |

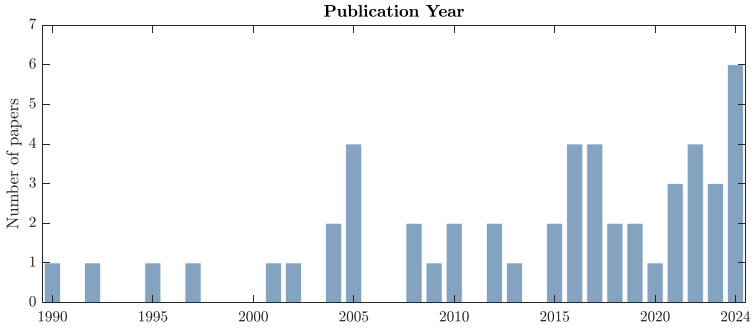



**Fig. 3.** Trend of publication years.

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 |

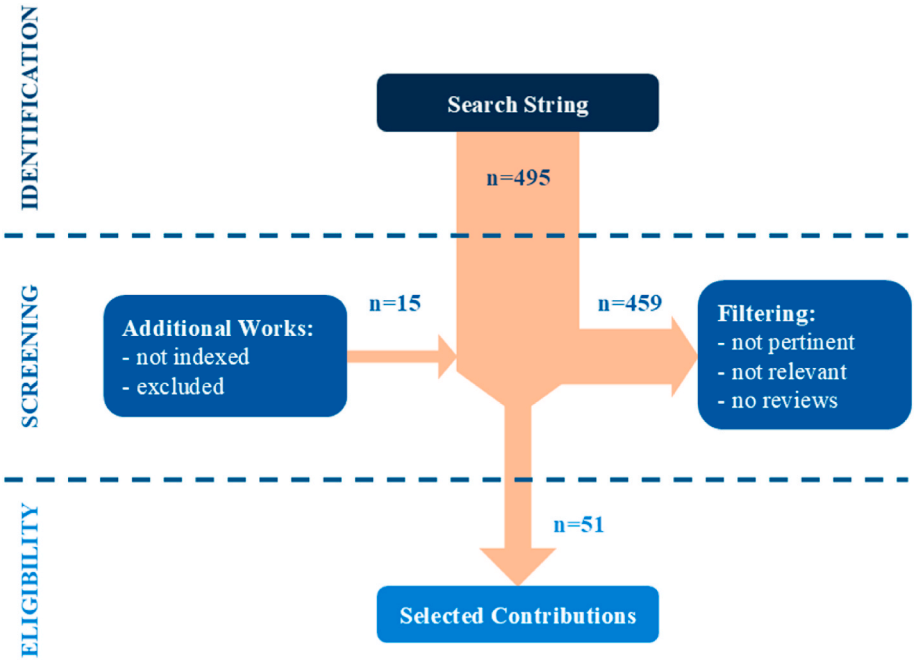



**Fig. 4.** Flowchart describing the selection process for systematic literature analysis.

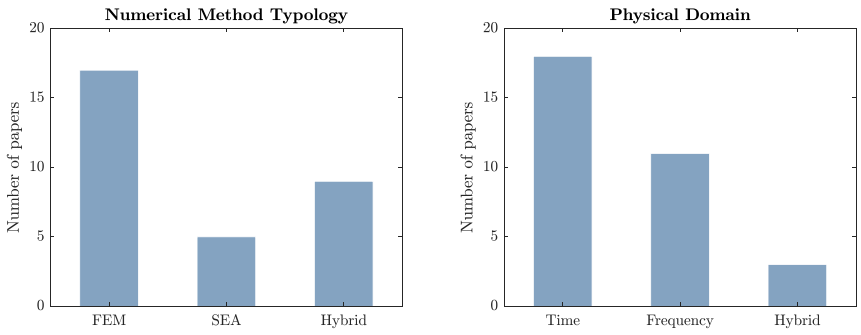



**Fig. 5.** Histograms inherent to the method typologies (on the left), and their domain (on the right) of the selected papers describing numerical methods for pyroshock simulation.

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

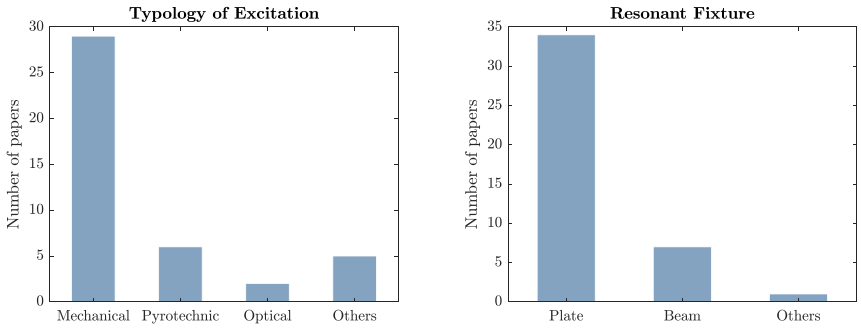



**Fig. 6.** Histograms inherent to the excitation techniques (on the left), and the adopted resonant fixtures (on the right) of the selected papers describing experimental test benches for pyroshock simulation.

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.

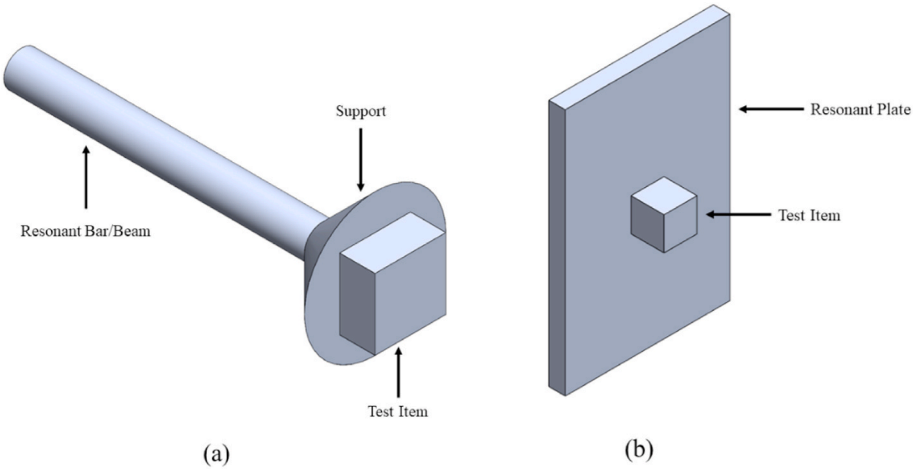



**Fig. 7.** Different typologies of resonant fixtures: (a) resonant bar/beam, and (b) resonant plate.

### 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

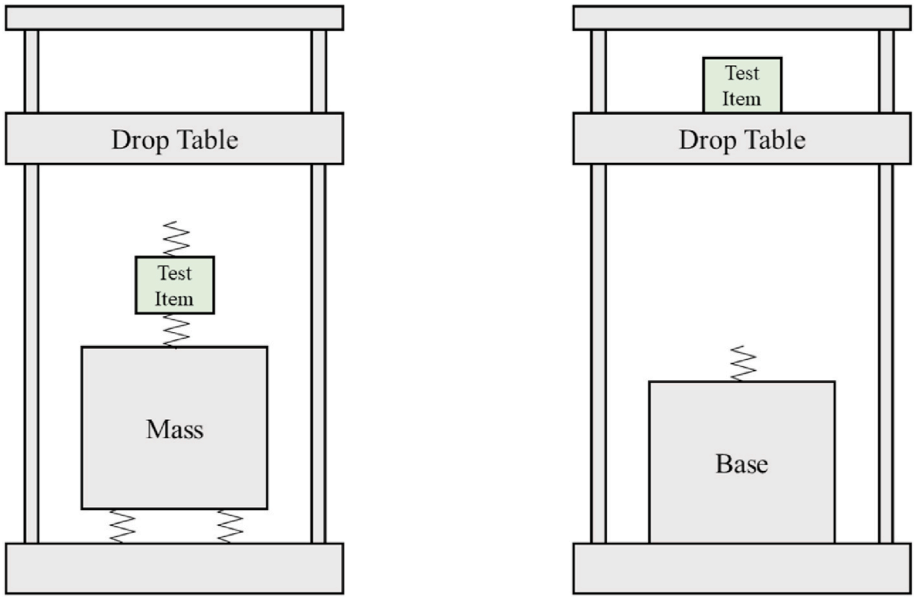



**Fig. 8.** Examples of drop tables for pyroshock testing.

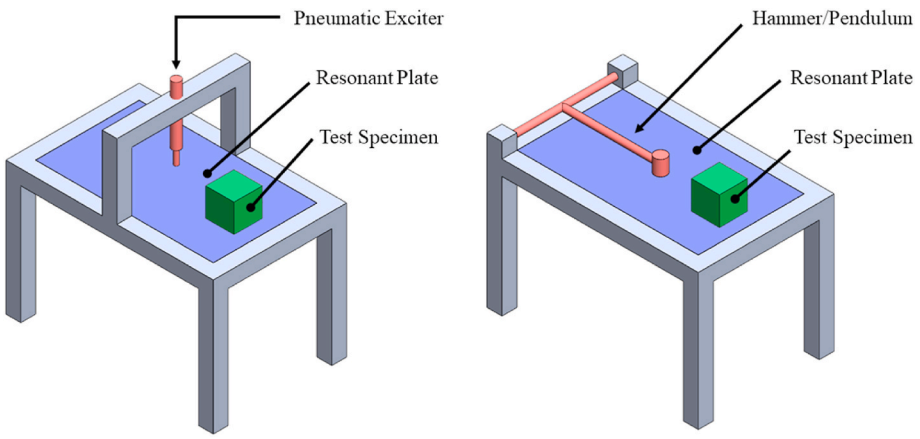



**Fig. 9.** Examples of pyroshock simulator exploiting mechanical excitation techniques: on the left, pneumatic exciter, and, on the right, hammer or pendulum.

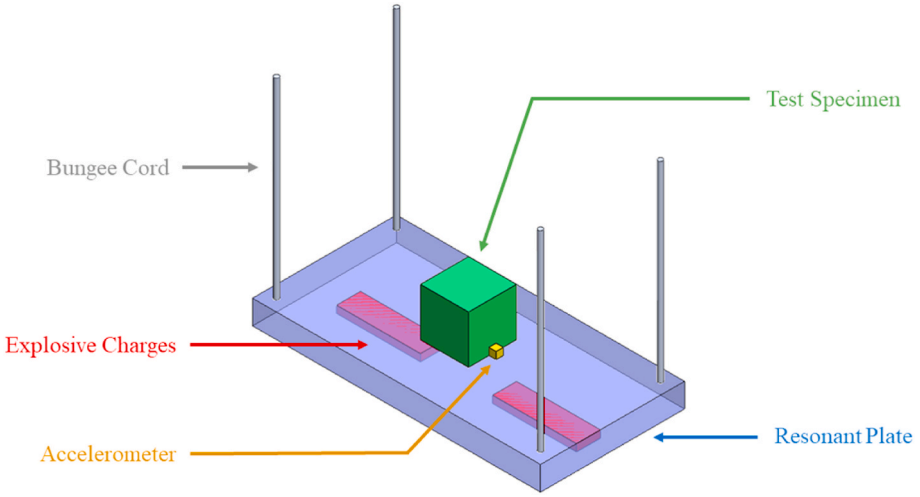



**Fig. 10.** Qualitative representation of a pyroshock simulator through explosive charges.

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

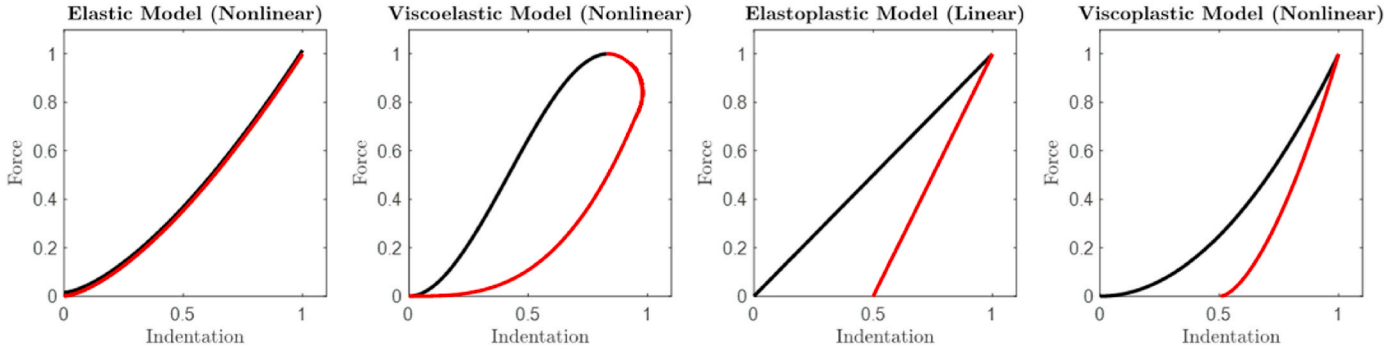



**Fig. 11.** Example of contact mechanics models classified by the force-indentation curve. The black and red curves respectively represent the compression and restitution phases composing the hysteresis cycle. (For interpretation of the references to colour in this figure legend, the reader is referred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

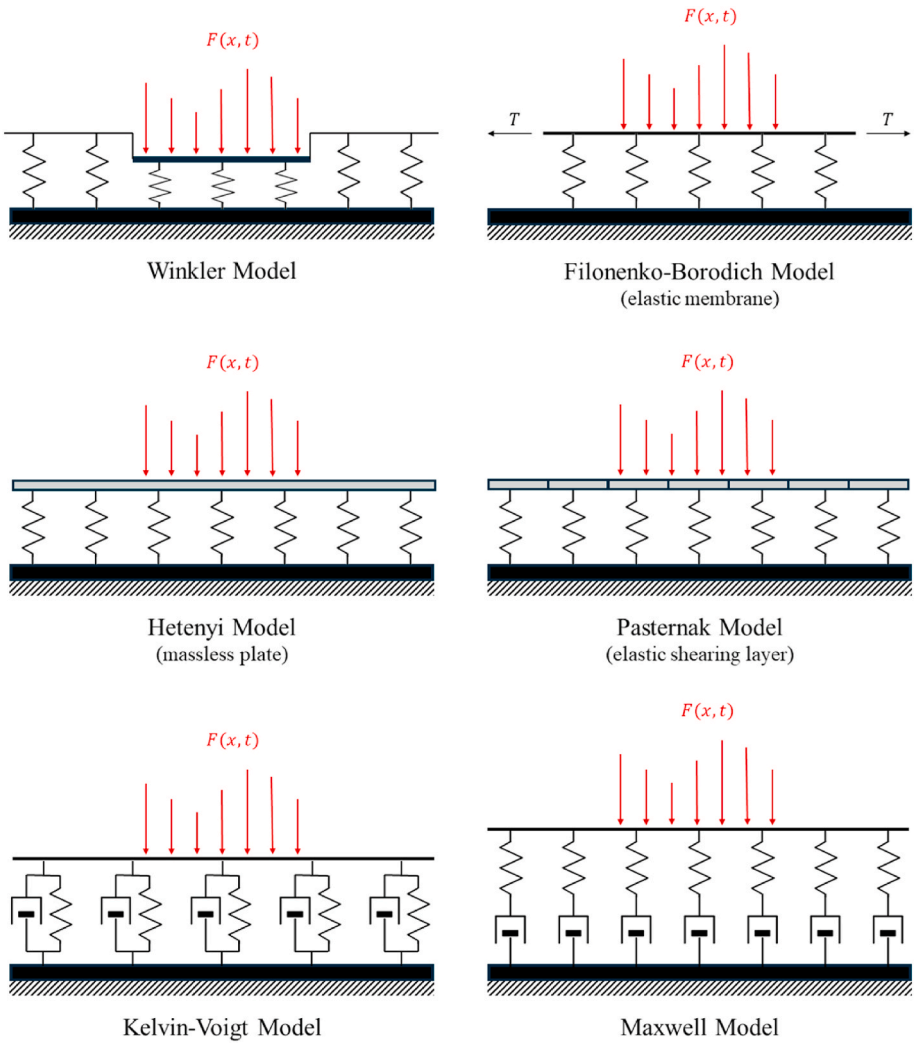



**Fig. 12.** Schematic representation of the main foundation models.

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.

## References

[1] A. Calvi, G. Aglietti, J. Albus, M. Bellini, D. Burtin, E. Cavro, J. Dupré, C. Fabriés, S. Fransen, D. Gangloff, ECSS-E-HB-32-26A spacecraft mechanical loads analysis handbook, ESA-ESTEC: Noordwijk, The Netherlands, 2013.
[2] H. Himelblau, J.E. Manning, D.L. Kern, A.G. Piersol, S. Rubin, Dynamic environmental criteria, NASA Techn. Handbook 7005 (2001) 249.
[3] J. Achenbach, Wave Propagation in Elastic Solids, Elsevier, 2012.
[4] V. Babuska, S.P. Gomez, S.A. Smith, C. Hammetter, D. Murphy, Spacecraft pyroshock attenuation in three parts, in: 58th AIAA/ASCE/AHS/ASC Structures, Structural Dynamics, and Materials Conference, American Institute of Aeronautics and Astronautics, Grapevine, Texas, 2017.
[5] J.-R. Lee, C.C. Chia, C.-W. Kong, Review of pyroshock wave measurement and simulation for space systems, Measurement 45 (2012) 631–642.
[6] MIL-STD-810F, Department of Defense Test Method Standard for Environmental Engineering Considerations and Laboratory Tests. Version F, US Government Printing Office, 2000.
[7] A.P. One, Pyroshock Testing Techniques, 2009.
[8] H. Himelblau, Pyroshock Test Criteria, 2011. NASA-STD-7003A.
[9] J.E. Alexander, Shock response spectrum-a primer. Sound & Vibration 43, 2009, pp. 6–15.
[10] C. Sisemore, Defining resonant plate shock test specifications in the time domain, Sandia National Lab, Albuquerque, NM (United States), 2019.
[11] ECSSSecretariat ESA, ESTEC Requirements&StandardsDivision, ECSS-E-ST-10-03C, Space Engineering-Testing, ESA Publications Division, Noordwijk, The Netherlands, 2012.
[12] N.T. Davie, V.I. Bateman, Pyroshock simulation for satellite components using a tunable resonant fixture, in: Phase 1, vol. 93, NASA STI/Recon Technical Report N, 1992 22975.
[13] N.T. Davie, V.I. Bateman, Pyroshock Simulation for Satellite Components Using a Tunable Resonant Fixture-phase 2, Sandia National Labs., Albuquerque, NM (United States), 1997.
[14] S.H. Abbas, J.-R. Lee, J.-K. Jang, Z. Kim, FPGA-based multipoint shock wave measurement system using LDVs for aerospace applications, in: 2016 IEEE Aerospace Conference, IEEE, 2016, pp. 1–6.
[15] W. Bae, J. Park, Optimization of pyroshock test conditions for aerospace components to enhance repeatability by genetic algorithms, Aerospace 11 (2024) 700.
[16] M. Choi, Experimental prediction of shock response spectra of point-wise explosive pyroshock in a space launcher composite structure using laser pulse excitation and in-line filtering, SAE Int. J. Aerospace 6 (2013) 65–69.
[17] D. Dilhan, A. Piquereau, L. Bonnes, J. Van de Veire, Definition and manufacturing of the pyroshock bench, in: 7th ESA/CNES International Workshop on Space Pyrotechnics ESTEC, 2008.
[18] A. García-Pérez, A. Ravanbakhsh, F. Sorribes-Palmer, G. Alonso, Structural shock verification by numerical analysis of the EPD payload units on board Solar Orbiter spacecraft, Acta Astronaut. 168 (2020) 282–292.
[19] M. Gherlone, D. Lomario, M. Mattone, R. Ruotolo, Application of wave propagation to pyroshock analysis, Shock Vib. 11 (2004) 145–156.
[20] B. Houshmand, A. Lacher, N. Juengel, L. Prasol, U. Von Wagner, E. Uhlmann, A novel excitation method for pyroshock simulation, J. Vib. Control 22 (2016) 4247–4258.
[21] J.H.-J. Hwang, A. Duran, Stochastic shock response spectrum decomposition method based on probabilistic definitions of temporal peak acceleration, spectral

energy, and phase lag distributions of mechanical impact pyrotechnic shock test data, Mech. Syst. Signal Process. 76 (2016) 424–440.
[22] M. Iadevaia, B. Van Hal, J.L. Riobbo, P. Sas, Using statistical energy analysis for shock pulse predictions, in: Proceedings of ISMA, 2002, p. 2342. Citeseer.
[23] T. Iwasa, Q. Shi, Simplified analysis model for predicting pyroshock responses on composite panel, J. Space Eng. 1 (2008) 79–90.
[24] J. Jeong, K. Kim, J. Lee, Development of a point pyroshock source simulator, Shock Vib. 2017 (2017).
[25] B.-S. Kim, J. Lee, Development of impact test device for pyroshock simulation using impact analysis, Aerospace 9 (2022) 407.
[26] S. Kiryenko, G. Piret, J. Kasper, ESA/ESTEC shock bench presentation, in: Spacecraft Structures, Materials and Mechanical Testing 2005, 2005.
[27] A. Lacher, N. Jüngel, U. von Wagner, A. Bäger, Analytical calculation of in-plane response of plates with concentrated masses to impact and application to pyroshock simulation, J. Sound Vib. 331 (2012) 3358–3370.
[28] J.-R. Lee, J.-K. Jang, M. Choi, C.-W. Kong, Visualization and simulation of a linear explosive-induced pyroshock wave using Q-switched laser and phased array transducers in a space launcher composite structure, Opt Laser. Technol. 67 (2015) 12–19.
[29] B. Li, Q. Li, B. Liu, Z. Niu, Z. Nangong, C. Zhao, Critical shock response spectrum of a beam under shock loading, in: International Conference on Offshore Mechanics and Arctic Engineering, American Society of Mechanical Engineers, 2016. V009T12A019.
[30] G. Liu, H. Luo, C. Yu, W. Zhang, G. Liu, H. Luo, C. Yu, W. Zhang, Study on pyroshock response of micro-satellite pyrotechnic cutter, Aero. Sci. Technol. 153 (2024).
[31] X. Lu, K. Jiang, S. Cheng, D. Su, H. Wang, Prediction and isolation of pyroshock in typical pyrotechnic device based on coupled modeling technique, Thin-Walled Struct. 177 (2022) 109393.
[32] V. Mittal, M. Patnaik, S. Narayan, D. Premkumar, Development of pyroshock simulation device (PSSD) for spacecraft application, J. Spacecraft Technol. 29 (2018) 11–18.
[33] R. Monti, P. Gasbarri, Dynamic load synthesis for shock numerical simulation in space structure design, Acta Astronaut. 137 (2017) 222–231.
[34] O.M.F. Morais, C.M.A. Vasques, Shock environment design for space equipment testing, Proc. Inst. Mech. Eng. G J. Aerosp. Eng. 231 (2017) 1154–1167.
[35] M. Remedia, G. Aglietti, M. Appolloni, A. Cozzani, A. Kiley, Virtual testing: a pre- and post-test tool for base-driven spacecraft testing, in: Aerospace Testing Seminar, 2017.
[36] Y. Sadkin, Spacecraft quasi-static test performed on a shaker, in: Environmental Testing for Space Programmes, 2004, pp. 203–208.
[37] P. Seefeldt, T. Spröwitz, J.T. Grundmann, E. Ksenik, E. Mikulz, S. Reershemius, K. Sasaki, M. Sznajder, Special testing and test strategies for unique space hardware developments, in: Proceedings of the International Astronautical Congress, IAC, 2018.
[38] D. Soine, T. Schoenherr, B. Witt, Resonant Plate Shock Test Response with Isolated Damping Bars, Sandia National Lab.(SNL-NM), Albuquerque, NM (United States), 2021.
[39] D.E. Soine, T.F. Schoenherr, A.J. Bouma, Resonant bar shock test equipment under offset loading. Conference Proceedings of the Society for Experimental Mechanics Series, 2024, pp. 79–84.
[40] D.E. Soine, T.F. Schoenherr, J.D. Heister, Evaluation of a multiaxis shock fixture concept, in: Society for Experimental Mechanics Annual Conference and Exposition, Springer, 2023, pp. 61–67.
[41] M. Sutra, D. Mesnier, A. Berlioz, B. Combes, Development of a simulation process of the behaviour of space equipment subjected to pyrotechnic shocks, based on characterization and environmental tests, in: Spacecraft Structures, Materials and Mechanical Testing 2005, 2005.
[42] L. Viale, A.P. Daga, A. Fasana, L. Garibaldi, On pyroshock tests for aerospace equipment qualification: a comprehensive parametric model for the simulation and the design of pyroshock test facilities, Int. J. Impact Eng. 180 (2023) 104697.
[43] L. Viale, A.P. Daga, L. Garibaldi, A. Fasana, Numerical modeling of a pyroshock test plate for qualification of space equipment, in: P. Rizzo, A. Milazzo (Eds.), European Workshop on Structural Health Monitoring, Springer International Publishing, Cham, 2023, pp. 990–999.
[44] L. Viale, A.P. Daga, A. Fasana, L. Garibaldi, others, Optimization of irregular-shaped resonant plates for pyroshock testing in the aerospace industry, in: Proceedings of ISMA 2024-International Conference on Noise and Vibration Engineering and USD 2024-International Conference on Uncertainty in Structural Dynamics, KU Leuven, Departement Werktuigkunde, 2024, pp. 740–748.
[45] X. Wang, W. Liu, X. Li, Y. Sun, The shock response prediction of spacecraft structure based on hybrid FE-SEA method, Appl. Sci. 11 (2021) 8490.
[46] X. Wang, W. Liu, J. Ding, Y. Sun, Y. Dang, Pyroshock response prediction of spacecraft structure in wide frequency domain based on acceleration FRF, Aerospace 9 (2022) 54.
[47] D. Wattiaux, O. Verlinden, C. Conti, C. De Fruytier, Prediction of the vibration levels generated by pyrotechnic shocks using an approach by equivalent mechanical shock, J. Vib. Acoust. 130 (2008).
[48] T. Yalçinkaya, B. Gürsoy, Numerical validation of a pyroshock test system and application to qualification tests, Aerospace 9 (2022) 400.
[49] Z. Hongda, D. Jifeng, L.I.U. Wei, H.A.O. Zhiwei, S.U.N. Yi, Q. Zhang, L.I.U. Yizhi, Simulator of pyroshock environment and effect rules of its adjustable parameters, Chin. J. Aeronaut. 33 (2020) 609–620.
[50] C. Sisemore, M.A. Spletzer, Design of a Resonant Plate Shock Fixture to Attenuate Excessive High-Frequency Energy Inputs, Sandia National Lab.(SNL-NM), Albuquerque, NM (United States), 2017.
[51] J.M. McGlaun, S.L. Thompson, M.G. Elrick, CTH: a three-dimensional shock wave physics code, Int. J. Impact Eng. 10 (1990) 351–360.
[52] M. Jonsson, Development of a Shock Test Facility for Qualification of Space Equipment, Department of Applied Mechanics, Göteborg, Sweden, 2012.
[53] C. Qian, Simulation of Mechanical Shock with Finite Element Analysis and Estimation of Shock Attenuation, 2021.
[54] A.İ. Küçükbayram, Analysis and Verification of a Pyroshock Test System, Master's Thesis, Middle East Technical University, 2021.
[55] N. Siam, Development of an Efficient Analysis Method for Prediction and Structural Dimensioning of Space Structures Subjected to Shock Loading, 2010.
[56] E. Gomez, Dynamic Response Predictions of Structures Subjected to Pyroshock Excitation, KTH Royal Institute of Technology, 2005.
[57] E. Dalton, B. Chambers, I.I. Chambers, Analysis and validation testing of impulsive load response in complex, multi-compartmented structures, in: 36th Structures, Structural Dynamics and Materials Conference, 1995, p. 1243.
[58] B. Troclet, B. Hiverniau, M.N. Ichchou, L. Jezequel, K. Kayvantash, T. Bekkour, J. B. Mouillet, A. Gallet, FEM/SEA hybrid method for predicting mid and high frequency structure-borne transmission, Open Acoust. J. 2 (2009).
[59] A.P. Daga, L. Viale, L. Garibaldi, A. Fasana, S. Marchesiello, Frequency domain convolutional model of a pyroshock plate for qualification of space equipment, AIP Conf. Proc. 2872 (2023) 120011.
[60] R. Ullio, P.C. Marucchi-Chierro, A. Spazio, Utilization of prediction methods in the shock environment evaluation, in: Spacecraft Structures, Materials and Mechanical Testing, 2001, p. 239.
[61] D.-O. Lee, J.-H. Han, H.-W. Jang, S.-H. Woo, K.-W. Kim, Shock response prediction of a low altitude earth observation satellite during launch vehicle separation, Int. J. Aeronaut. Space Sci. 11 (2010) 49–57.
[62] J. Liu, L. Yang, X. Zhang, R. Yan, X. Chen, Intelligent time-domain parameters matching for shock response spectrum and its experimental validation in active vibration control systems, Shock Vib. 2019 (2019) 1–16.
[63] R.J. Pinnington, D. Lednik, Transient statistical energy analysis of an impulsively excited two oscillator system, J. Sound Vib. 189 (1996) 249–264.
[64] B.Y. Mao, S.L. Xie, M.L. Xu, X.N. Zhang, G.H. Zhang, Simulated and experimental studies on identification of impact load with the transient statistical energy analysis method, Mech. Syst. Signal Process. 46 (2014) 307–324.
[65] A. García-Pérez, F. Sorribes-Palmer, G. Alonso, A. Ravanbakhsh, Overview and application of FEM methods for shock analysis in space instruments, Aero. Sci. Technol. 80 (2018) 572–586.
[66] A.E.H. Love, A Treatise on the Mathematical Theory of Elasticity, Dover Publications, New York, 1944, p. 1.
[67] L.D. Landau, E.M. Lifshitz, Course of Theoretical Physics, Elsevier, 2013.
[68] B. Leroy, Collision between two balls accompanied by deformation: a qualitative approach to Hertz's theory, Am. J. Phys. 53 (1985) 346–349.
[69] D. Gugan, Inelastic collision and the Hertz theory of impact, Am. J. Phys. 68 (2000) 920–924.
[70] H. Ghaednia, X. Wang, S. Saha, Y. Xu, A. Sharma, R.L. Jackson, A review of elastic–plastic contact mechanics, Appl. Mech. Rev. 69 (2017) 060804.
[71] A.D. Kerr, Elastic and viscoelastic foundation models, J. Appl. Mech. 31 (1964) 491–498.
[72] D. Younesian, A. Hosseinkhani, H. Askari, E. Esmailzadeh, Elastic and viscoelastic foundations: a review on linear and nonlinear vibration modeling and applications, Nonlinear Dyn. 97 (2019) 853–895.
[73] E. Winkler, Die Lehre von der Elasticitaet und Festigkeit: mit besonderer Rücksicht auf ihre Anwendung in der Technik, für polytechnische Schulen, Bauakademien, Ingenieure, Maschinenbauer, Architecten, etc, H. Dominicus, 1867.
[74] M.M. Filonenko-Borodich, Some approximate theories of elastic foundation, Uchenyie Zapiski Moskovskogo Gosudarstvennogo Universiteta Mekhanika 46 (1940) 3.
[75] M. Hetenyi, A general solution for the bending of beams on an elastic foundation of arbitrary continuity, J. Appl. Phys. 21 (1950) 55–58.
[76] P.L. Pasternak, On a New Method of Analysis of an Elastic Foundation by Means of Two Foundation Constants, Gos. Izd. Lit. Po Strait I Arkh, 1954.
[77] W. Flügge, Viscoelasticity, Blaisdell Publ, Co., Waltham, Mass., USA, 1967, p. 127.
[78] K.H. Hunt, F.R.E. Crossley, Coefficient of restitution interpreted as damping in vibroimpact, J. Appl. Mech. 42 (1975) 440–445.
[79] W.J. Stronge, Unraveling paradoxical theories for rigid body collisions, J. Appl. Mech. 58 (1991) 1049–1055.
[80] C. Zener, The intrinsic inelasticity of large plates, Phys. Rev. 59 (1941) 669.
[81] G. Weir, S. Tallon, The coefficient of restitution for normal incident, low velocity particle impacts, Chem. Eng. Sci. 60 (2005) 3637–3647.