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IMPACT INDUCED HIGH FREQUENCY VIBRATIONS: OPTIONS FOR A UNIFIED APPROACH FOR THE DESIGN OF COMPONENTS

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ABSTRACT

The components of a nuclear power plant (NPP) can be subjected to high-frequency impact-induced vibrations under loading such as airplane crash (APC) or dropped weight. These impact-induced vibrations propagate from the impact location through the structure into their interior structures and components and can affect the functionality of safety-related electrical and instrumentation & control (I&C) equipment. This paper reviews available experimental studies, design methods and practices and discusses the issues related to these methods for electrical cabinets. Furthermore, it highlights the need for a unified design approach for safety-related components subjected to high-frequency acceleration.

INTRODUCTION

Currently, there is no unified approach for dealing with impact-induced vibrations. The analysis of these vibrations is sometimes performed according to seismic analysis methods, see e.g., the requirement in RCC-CW (2018). However, the in-structure response spectra (ISRS) calculated for the cabinet location and the response spectra calculated for the component location within the cabinet (i.e., in-cabinet response spectra, ICRS) for seismic loading are significantly different from those obtained for APC loading. The latter generally exhibit high magnitude acceleration in the high frequency range. Some studies indicate that the accelerations at high frequencies are associated with small displacements and negligible energy. On the other hand, even small displacements at high frequencies with corresponding high accelerations can affect the functionality of sensitive devices and lead to their failure. For example, a recent report of a reactor trip at the Farley 1 reactor (Ballesteros et al. 2023) demonstrates how a trivial accident resulting from the dropping of a “floor tile” near a relay panel could lead to a generator trip.

The experience gained from the few available experimental studies (listed in the state-of-the-art section) on the behavior of components subjected to high-frequency loading is partially contradictory, which emphasizes the importance of understanding the energy dissipation along the vibration propagation path. In addition, the connection to the shaking table or to the tested/impacted structure has been shown to have an influence on the test results and must be consistent with the actual mounting conditions of the cabinets in NPPs.

This publication provides a summary of the available experiments and design methods for components (especially electrical cabinets) subjected to high-frequency impact-induced vibrations. It then highlights the issues associated with these current studies and discusses the need for a unified design approach for these safety-related components.

STATE-OF-THE-ART

A more comprehensive review of the state-of-the-art in design methods and practices, as well as the experimental studies for structures, systems, and components SSCs subjected to impact-induced high-frequency vibrations is published by the authors in Ghadimi Khasraghy et al. (2023). A brief summary of this review is provided in this paper.

Experimental Studies

The behavior of electrical cabinets subjected to high-frequency seismic motions has been extensively studied (e.g., EPRI reports in the list of references). However, there are only a few published experiments on SSCs subjected to high-frequency impact-induced vibrations, including vibration tests carried out on equipment and those on reinforced concrete mock-up structures.

Full-scale experiments were performed on a shaking table with a typical switchgear used by the NPP vendor Areva, which concluded that the high-frequency content does not cause any damage to the switchgear (Fila et al. 2011) and is filtered out by local friction or yielding at the component connection to the structure.

The influence of the equipment anchorage on the filtering of high-frequency vibrations has been analytically evaluated by Hervé (2014). Different signal processing methods were considered in this study. A new method based on a nonlinear elastic single-degree-of-freedom system combined with a spectral displacement method was proposed and its application was discussed in Hervé at al. (2016).

As part of the IMPACT project (phase III) organized by VTT Technical Research Centre in Espoo (Finland), a so-called "V" test series on the vibration propagation and damping of different types of reinforced concrete structures subjected to impact loading was performed. Twelve tests were carried out on four mock-ups, which are documented in Saarenheimo et al. (2015), Vepsä et al. (2017), Saarenheimo et al. (2018), and Borgerhoff et al. (2019).

The Nuclear Energy Agency (NEA) launched the third phase of the benchmark project IRIS (**I**mproving **R**obustness assessment methodologies for structures **I**mpacted by mi**S**siles) in 2016. In this project the transmission of impact-induced vibrations in reinforced concrete structures was investigated, see EDF (2017) and Vepsä et al. (2016). The test mock-up is shown in Figure 1.

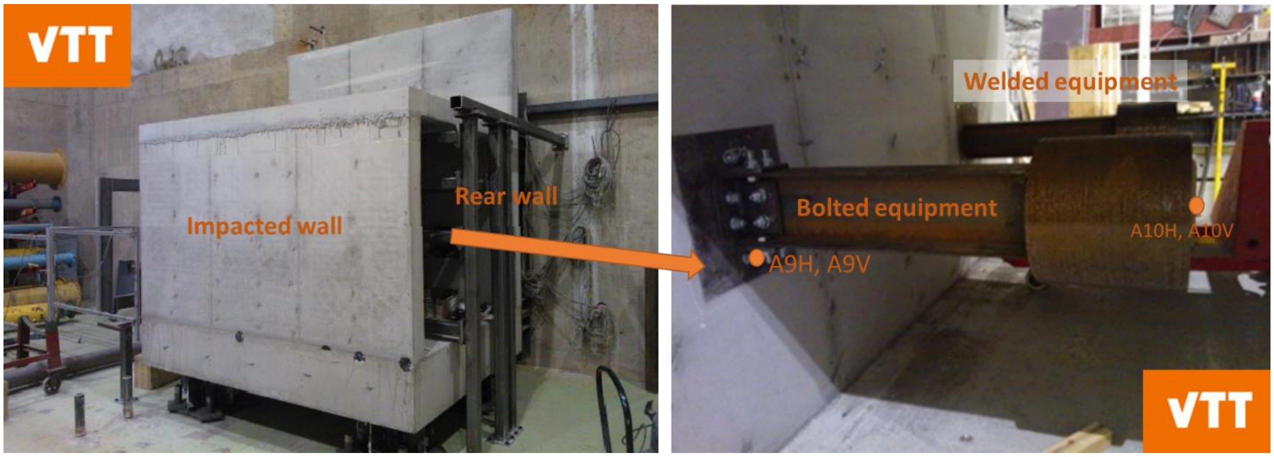


Figure 1. Experimental mock-up of the IRIS Phase 3, see Vepsä et al. (2016)

A qualification method for I&C cabinets using required response spectra (RRS) was presented by Moussallam et al. (2022). A full-scale cabinet was tested on a shaking table for both APC and earthquake loading. It was observed, that contrary to other studies (e.g., Fila et al. (2011)), the high-frequency vibrations were indeed transmitted through the cabinet structures with a significant amplification.

Gratiet et al. (2022) briefly reported some tests carried out on equipment at Électricité de France (EDF) from 2015 to 2018, including a low tension LT switchboard (for accelerations up to 5.7 g). They did not observe mechanical damage to the equipment. However, some of the equipment experienced contact chattering at high magnitudes.

Vibration tests and analyses on components have also been conducted by the Nuclear Regulatory Authority of Japan (NRA 2021), which showed that the high frequency vibrations can be amplified inside the equipment. The ICRS amplitude can be lower when the maximum displacement is smaller than the effective gap at the connection. For the floor displacements greater than the available gap, higher spectral amplitudes are observed due to local impacts resulting in high-frequency oscillations.

A study on the effect of high frequency seismic motions on electrical cabinets (Singh and Gupta (2019)) concluded on the amplification of the vibration through the cabinet structures due to local impacts at the connection to the shaking table. Jeon et al. (2021) presented the sensitivity of the cabinet to high-frequency seismic motions by adding mass to represent the electrical instrumentation. It was concluded that the dynamic characteristics of the cabinet may result in functional failure during and after high-frequency earthquakes.

Guidelines and Provisions

High-frequency impact-induced vibrations are treated by various approaches. One approach (e.g., RCC-CW 2018) is to treat them similarly to seismic induced vibrations using corresponding analysis methods. Since the ISRS and ICRS under APC loading are different in terms of frequency and energy content from those obtained under seismic loading, a specific methodology is more appropriate to analyse APC induced vibrations for both integrity and functionality verification.

The intended design of the equipment (structural integrity or functionality) defines its acceptance criteria. The high frequency accelerations generally do not affect the structural integrity of SSCs. However, both low and high frequency input motions can affect the functionality of sensitive electrical components. A common approach for assessing the structural integrity of components is the truncated ISRS approach (IAEA (2018)), originally introduced by Krutzik (1985). The displacement and acceleration response spectra are calculated at the location of the component. Considering a spectral displacement limit value (e.g., 1.0 mm, for which vibrations can be absorbed by gaps or elasto-plastic (nonlinear) deformations between the component and its support), it is possible to define a relevant frequency range for its design. However, the full (non-truncated) frequency range must be considered in order to evaluate the functionality of sensitive equipment and components, since high-frequency vibrations can eventually cause relays and switches to trip.

According to the guideline of the German Reactor Safety Commission (RSK) for pressurized water reactors (RSK (1981)), the integrity of components and systems in the reactor building should be verified by assuming a static equivalent load resulting from an acceleration of ± 0.5 g in the horizontal and vertical directions for the frequency range up to 16 Hz. In addition, it must be ensured that relative displacements of up to 1 mm between the component and its support can be absorbed by a gap and/or elasto-plastically for frequencies above 16 Hz.

A new RSK (2021) report summarizes the results of studies on the effects of a large commercial APC on German NPPs. It uses a multi-step procedure to verify the integrity and, if necessary, the functionality of the components. It suggests that for (spectral) displacements < 1 mm, the verification could also be concluded positively, since such small displacements certainly do not lead to damage due to the gaps in the supports and the elasticity in the components.

The Nuclear Energy Institute (NEI (2011)) suggests evaluating the shock damage in terms of the damage footprint, which implies that all equipment within the footprint is assumed to fail at the time of impact. For relays, circuit breakers and control panels, a median fragility limit of 27 g is proposed.

PROBLEM STATEMENT AND NEED FOR A UNIFIED DESIGN APPROACH

Experimental Studies

The few published experimental studies on the behavior of the components (especially electrical cabinets) do not provide a detailed description of the experimental setup and their mounting/anchoring to the shaking table. Some of these existing studies concluded on the irrelevance of high-frequency content leading to small displacements filtered by their mounting. In contrast, some other experimental evidence indicated that these accelerations can be magnified by the cabinet structures. These contradictory conclusions highlight the importance of understanding the physical phenomena and the vibration path though the structure, at the structure-to-cabinet interface, and within the cabinet.

Figure 2 shows the acceleration response spectra of the cabinets tested by Fila et al. (2011) and Moussallam et al. (2022). These curves are digitalized from the published curves and may slightly differ. The study by Fila et al. (2011) is performed for an input excitation of less than 1 g. The high frequency peak at about 25-30 Hz (red circle in the figure) is not observed in the measured response at the equipment level. However, there is a high amplification of the acceleration at the frequencies between10 and 20 Hz. The experiments of Moussallam et al. (2022) show spectral accelerations of up to 10 g for the load case LC4 at the table. Contrary to the previous study, the high frequency content was amplified at the top of the cabinet at frequencies between 70 and 90 Hz. This experiment showed a significant amplification of the acceleration at the frequencies above 20-40 Hz.

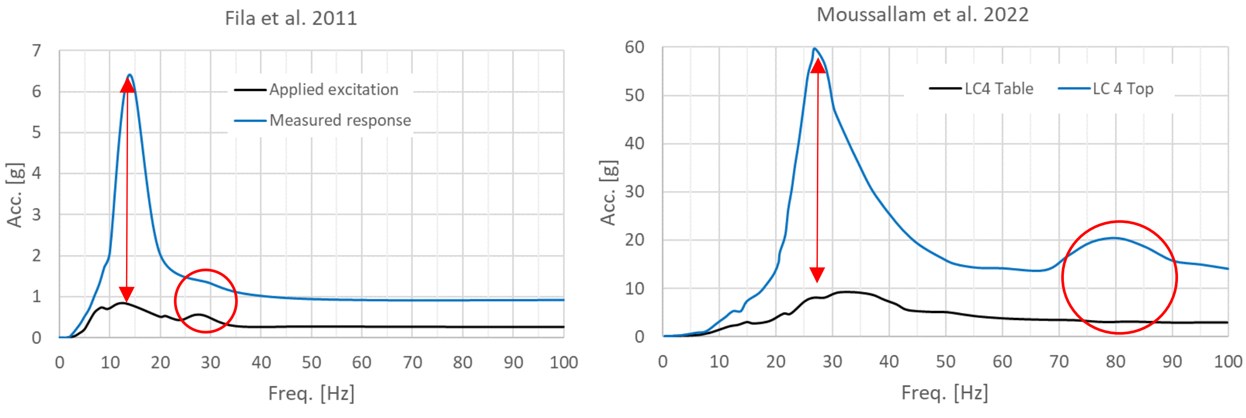


Figure 2. Comparison of experimental acceleration response spectra

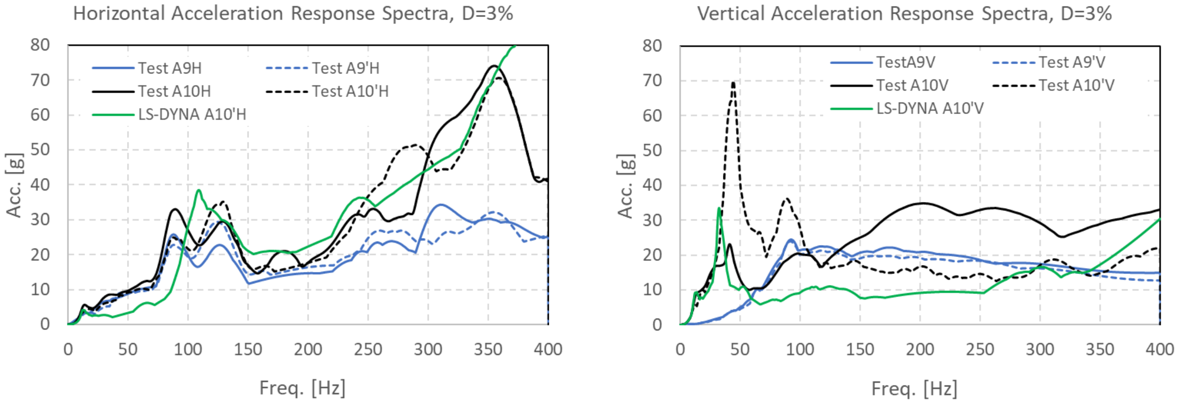
The vibration tests carried out on “reinforced concrete” mock-ups highlighted the difficulty of achieving the desired (near-rigid) boundary conditions in such experiments. Additionally, these studies questioned the appropriateness of using accelerations in the design and re-evaluation of components.

Guidelines and Provisions

Currently, the IAEA approach appears to be the most reasonable for treating the high-frequency impact-induced vibrations based on the intended design of the components (integrity or functionality). However, when using this approach to truncate the acceleration response spectra based on a spectral displacement limit, the exact mounting and the support (e.g., effective gap) of the components has to be considered. The full untruncated ISRS should be considered for the functionality of sensitive components. When filtering the ISRS using the approach based on a spectral displacement limit, care should be taken to preserve (and not to filter) significant portion of the signal energy.

Figure 3, left, shows an example of ISRS at the equipment location of the IRIS 3 benchmark project. The ISRS are obtained from the measured acceleration time histories for 3% damping according to the ASCE 4-16 (2017) recommendations (response level 1 for electrical cabinets and other equipment). The curves for A9H and A10H show the plot of the horizontal acceleration response spectra at the anchorage plate (rear wall) of the equipment as shown in Figure 1 and those measured at the cylindrical mass of the "bolted equipment", respectively. The curves for A9'H and A10'H correspond to the accelerations of the "welded equipment".

The horizontal accelerations show amplification at frequencies above 70 Hz (compared to A9H to A10H, and A9'H to A10'H). The vertical accelerations are shown on the right side of the Figure 3. These show amplification already at low frequencies. However, the welded equipment shows higher peaks compared to the bolted one in the vertical direction. This may emphasize the higher energy absorption of the bolted equipment compared to the welded one. On the other hand, the bolted equipment shows higher acceleration peaks at frequencies above 120 Hz.



Bolted equipment: A9, at anchor plate, and A10 at the equipment mass.
Welded equipment: A9' to A10', at anchor plate, and A10 at the equipment mass.
H: horizontal direction, V: vertical direction

Figure 3. Acceleration response spectra of the IRIS 3 equipment

The numerical evaluation of the IRIS Phase 3 mock-up using explicit finite element analyses with LS-DYNA software is presented in Ghadimi Khasraghy et al. (2019). The green curves plotted in the Figure 3 for the sensor A10, which is attached to the cylinder mass of the pseudo-equipment, agree well with the experimental measurements.

The horizontal acceleration response spectrum is filtered as shown in Figure 4 considering an allowable spectral displacement of 0.5 mm and 1 mm by applying the IAEA truncated approach in order to show the sensitivity of the chosen spectral displacement. For the spectral displacement limit of 0.5 mm, the representative acceleration is almost 10 times higher than in the case where the spectral displacement limit of 1 mm is used. When using a 1 mm spectral displacement limit, a significant part of the signal kinetic energy is lost. The figure also shows the application of a filter based on 90 % of the ratio of the spectral kinetic energy cumulated up to a resulting cut-off frequency to the total cumulative spectral kinetic energy. In this case, to account for a kinetic energy ratio of 90 %, accelerations up to 80 g must be considered, which is about 20 times higher than the case where the spectral displacement limit of 1 mm is used.

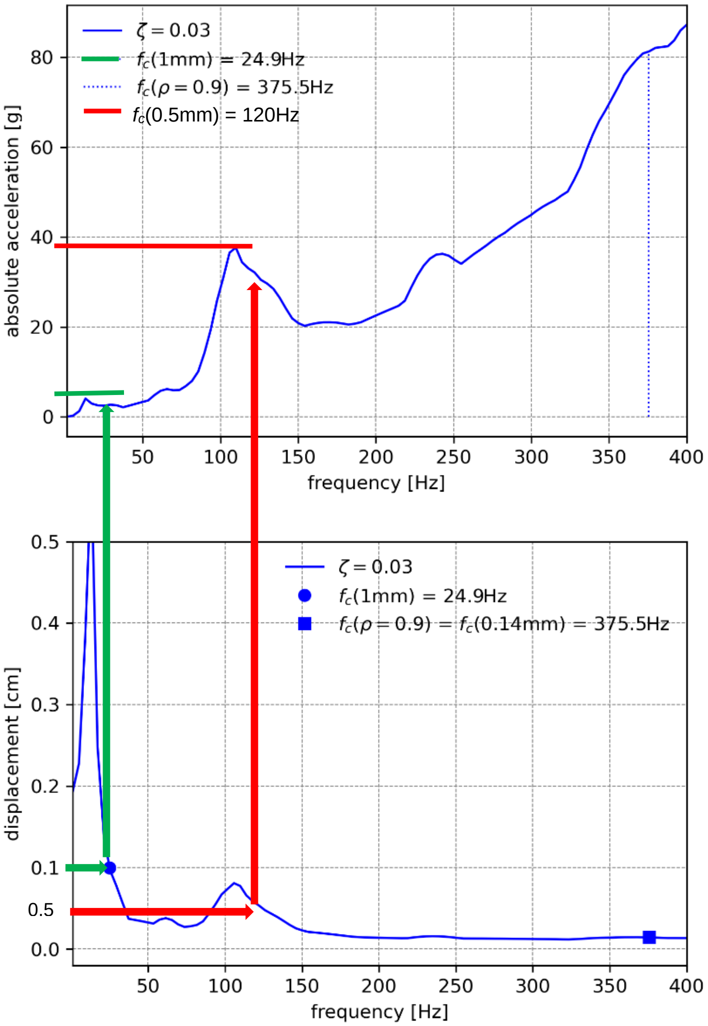


Figure 4. Truncated ISRS, application to the IRIS 3 calculation for the sensor A10'H

Applied Loading

The applied loading /excitation is typically obtained from finite element analyses of the APC on a nuclear building. The accelerations are then calculated at the location of the components on different floors. Thus, the ISRS required for the design depend on the structure and the location of the equipment within the building. Therefore, it is not possible to define a governing load for equipment design. Additionally, due to the confidentiality of the APC loading, experimental and numerical studies are often published using normalized loading curves and it is difficult to assess their suitability for other building types.

Nonlinearities at Structure to Component Interface

Despite a common argument about the influence of gaps and nonlinearities in filtering high-frequency vibrations, it is important to note that such small gaps can potentially amplify these accelerations due to local impacts once the existing gap is closed. On the other hand, in seismically qualified anchorage systems, the annular gap between the anchor plate and the steel anchor is typically filled to provide a uniform distribution of shear forces. Avoiding the gaps can be considered as the current practice in seismic engineering, which is contrary to the idea of filtering the high-frequency vibration due to the presence of gaps. Therefore, it is very important to use realistic mounting setup for experimental and numerical studies. Understanding interface nonlinearities (e.g., gaps, plasticity, sliding, and cracking) is critical to impact-induced vibrations analysis.

CONCLUSION

This paper discusses the state-of-the-art in design methods for SSCs subjected to impact-induced high-frequency vibrations and the need for a unified design approach. The propagation path of the impact-induced high-frequency vibrations through the structures, the structure-to-cabinet interface, and within the cabinets must be investigated in order to better understand the energy dissipation and to improve the verification methodology according to the design objective (structural integrity or functionality).

A review of the available experimental studies shows that the understanding of the physical phenomena (vibration path and a possible energy dissipation) needs to be improved. In addition, the support conditions, the connection to the shaking table, as well as the geometric nonlinearities must be understood and kept consistent with the actual mounting conditions of the electrical cabinets in NPPs.

Approaches to the treatment of high-frequency impact-induced vibration are typically based on the evaluation of the acceleration time-histories and their response spectra at the equipment location. Using a truncated acceleration approach based on a spectral displacement limit, a large portion of the signal energy may be neglected. The exact mounting of the equipment must be considered in such an approach. In addition, it is important to consider the intended design of the components (integrity or functionality).

A research collaboration of the authors on this topic will focus on the discussed shortcomings and the development of a unified approach for the design and qualification of electrical cabinets subjected to seismic and high-frequency impact-induced vibrations.

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