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DEVELOPMENT AND IMPLEMENTATION OF A QUALIFICATION METHODOLOGY FOR I&C COMPONENTS TO AIRPLANE CRASH INDUCED VIBRATIONS

Nadim Moussallam[1], Jürgen Dennerlein[2], Christiane Graf[2], Michael Goth[3], Karla Davina Liebig[2], Anthony Darraba[4]

[1] Expert engineer, Framatome, Lyon France (nadim.noussallam@framatome.com)
[2] Expert engineer, Framatome, Erlangen Germany
[3] Engineer, Framatome, Erlangen Germany
[4] Expert engineer, EDF, Lyon France

ABSTRACT

The present paper describes a method specifically developed for qualifying electrical and instrumentation and control (I&C) equipment to “Airplane Crash” (APC) induced vibration loads. In particular, the inherent characteristics of an APC that differentiate it from a seismic excitation are acknowledged. The method is illustrated with the results of a first test campaign applying it.

INTRODUCTION

In the past twenty years, the “Airplane Crash” (APC) induced vibrations have become a significant part of the design and qualification of nuclear power plants (NPP) equipment. The approach to addressing it is not yet unified. A typical approach in the European industry, is to calculate APC Floor Response Spectra (FRS) in the same way as FRS for Design Basis Earthquake (DBE). The equipment is then qualified with shaking table tests using the procedures defined for DBE in qualification codes such as RCC-E (2019) or IEC 60980 (2020).

Even though APC induced vibrations are partly comparable to seismic loads in the sense that both imply a dynamic response of the structure that produces an imposed movement at the equipment anchorages, some fundamental differences exist. First the directionality of APC induced vibrations is more pronounced than the one of earthquakes, the structural response being obviously stronger in the impacting direction of the airplane than in the two normal ones. In addition, the strong motion duration induced by an APC is typically less than 1 s, compared to about 10 s for earthquakes. And finally, the frequency range of APC induced vibrations is generally higher than the one of earthquake induced vibrations. Thus, the raw adaptation of DBE testing methods to the case of APC induced loads leads to unrealistically conservative testing parameters that are deemed not appropriate.

This paper describes a) the present state of the art, b) the concept of a proposed new APC qualification methodology, complementary to the seismic qualification, highlighting the differences between both approaches and c) the application of this concept to the case of an I&C cabinet and the return of experience associated to it.

PRESENT STATE OF THE ART

Several countries have developed specific methodologies to assess the damage induced by an APC on safety classified equipment but most of these countries do not make their methodologies public. One exception to this rule is the United States of America (USA). The requirement to include the impact of a large commercial aircraft as a beyond design-basis event in the design of new nuclear power plant was formalized by the Nuclear Regulatory Commission in NRC (2009). To answer this requirement, the Nuclear Energy Institute (NEI), together with the Electric Power Research Institute (EPRI) and the Engineering & Research (ERIN), have developed the guiding document NEI (2011). This document provides an assessment methodology for equipment needed to ensure the heat removal capacity in the event of an airplane crash. It consists in assessing the damage footprint in the plant within which certain classes of equipment must be assumed to be lost. The damage footprint is determined by the distance to the impact point and is function of the equipment category and its expected generic median fragility (i.e., 27g for control panels).

This approach is sometimes questioned as it does not account for such specificities as possible resonance between the structural response to the APC and the equipment response. It also does not consider the potential weakness of some electrical components to excitation within a certain range of frequencies. Illustration of such dependency is given in Figure 1 for a relay tested by Framatome with gradually increasing sine excitation. The relay is found to chatter in a given frequency range for a given excitation amplitude. The failure extends to a broader frequency range as the amplitude is increased.

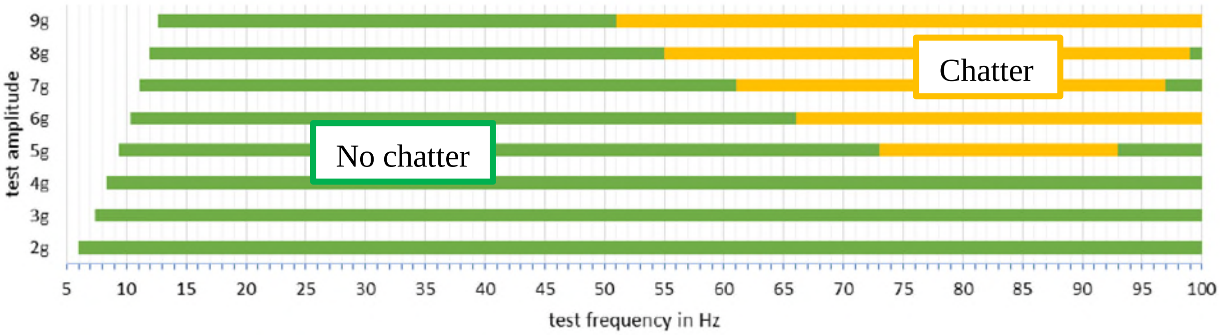


Figure 1. Performance of a relay submitted to gradually increasing sine excitation as a function of frequencies

The mostly used alternative to the footprint method is the one described in IAEA (2003) and consists in generating APC induced vibration FRS. Envelop FRS resulting from APC induced vibrations are generated and then used for qualifying the equipment. In some cases, both DBE and APC spectra were enveloped to produce a single set of Required Response Spectra (RRS) for the qualification. The cumulation of the "low" frequency excitation content of the earthquake and the "high" frequency excitation content of the APC sometimes leads to challenges for implementing it with a single shaking table test. For a cabinet supporting electrical components, there is also the risk that the low frequency excitation modifies the response of the frame through yielding or bolts loosening and that the excitation at high frequency, that should have reached the inner components otherwise, is filtered out.

Finally, a common practice in several countries, acknowledged by IAEA (2003) and documented in Vlaski (2013) and Hervé (2014) is the use of a displacement threshold to filter out the high frequency content of the APC excitation. The movements associated with low displacements are either considered not damaging for the mechanical components or are said to be physically filtered out by slight sliding within the anchorages or gap openings at bolted connections. A limit to this practice is constituted by the electrical and I&C equipment, that can be sensitive to excitation at high frequency and that is located within robust and well anchored cabinet that do not yield nor slide under APC loads. For such equipment, the response spectra method remains the reference approach.

CONCEPT OF THE PROPOSED METHODOLOGY

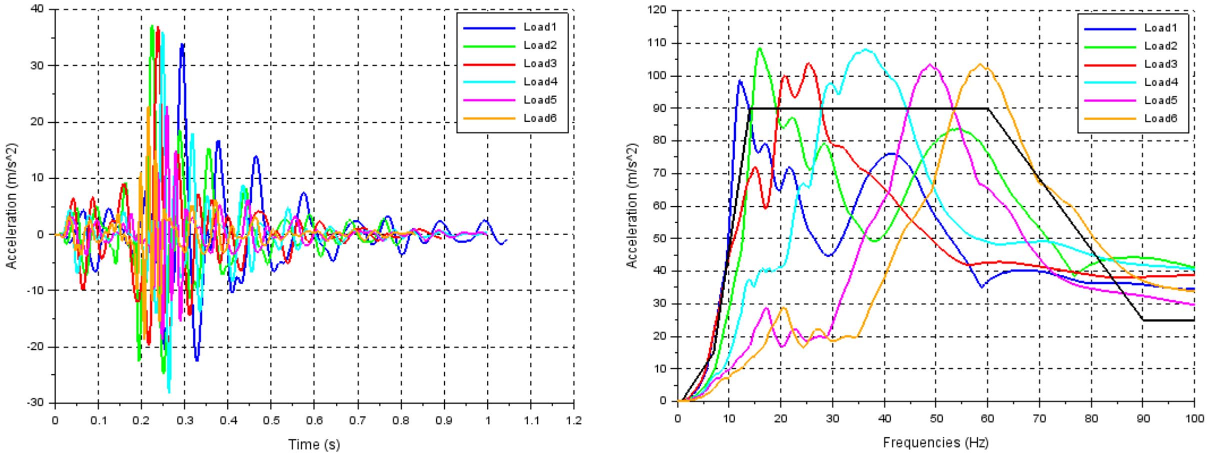
Determination of APC Required Response Spectra (RRS)

APC induced vibrations are significantly different from earthquake excitation in terms of frequency content, directionality and duration. The default or minimal values of test duration or strong motion excitation duration given in the code requirements concerning the qualification of equipment by shaking table tests are typically not appropriate for representing APC. Some codes, such as IEC (2020), specify that the duration of the strong motion portion of each test shall be at least equivalent to the strong motion portion of the original time history used to obtain the RRS. The methodology proposed here is in phase with this approach.

The starting point of the analysis is naturally the computation of the building dynamic response to a set of APC scenarios. This set of scenarios generally includes impacts on external walls in both horizontal directions and impacts on the roof with a significant vertical component. At each position within the building and for each scenario, a 3-dimensionnal set of acceleration time histories is calculated using a finite element model of the buildings. As for seismic excitation, floor response spectra are generated by enveloping the oscillator response spectra corresponding to the time histories at representative positions on a given floor and for all APC scenarios. After broadening of these response spectra peaks, they are identified as the Required Response Spectra (RRS) for the equipment qualification. For each floor, or part of floor, there is one APC RRS in each direction. Because different scenarios, different distances to the impact point and different positions on the floor are enveloped together, the resulting RRS is large, covering a range, for example, between 10 and 100 Hz.

Generation of representative sets of Required Acceleration Time Histories (RATH)

A reduced number of calculated acceleration time histories from the building APC calculation is then selected and scaled up so that, together, their response spectra cover the RRS. As an example, Figure 2 gives a set of 6 scaled acceleration time histories (in colours) as well as the comparison of their response spectra to the RRS (in black).

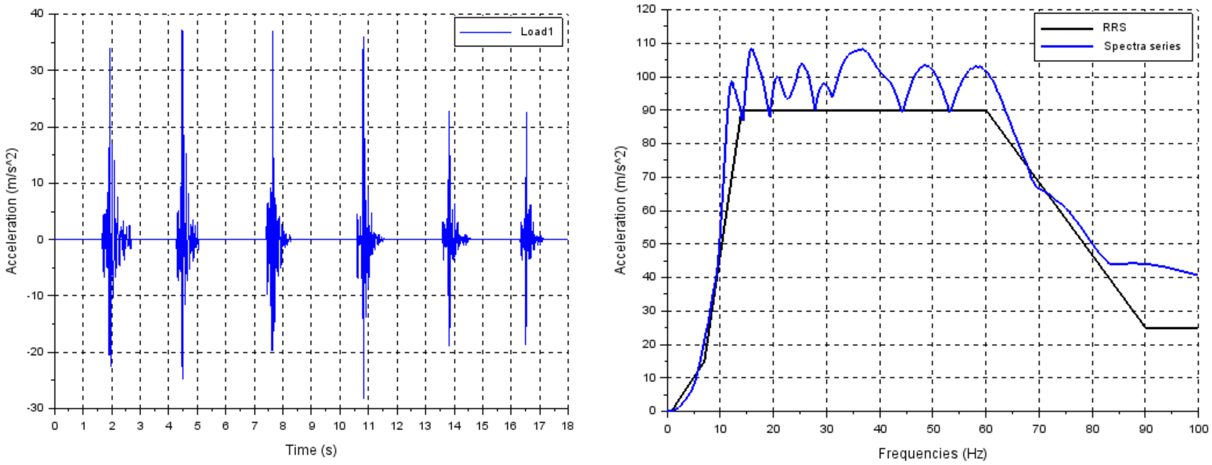


a) Time histories b) Response spectra

Figure 2. Scaled acceleration time histories and associated response spectra compared to the target RRS (in black)

The selection and scaling of time histories may be made independently in the three directions if the RRS are different in the three directions. A single selection is made if the RRS are the same in two or three directions. If bi-axial or tri-axial testing is foreseen, the same number of time histories must be generated for each direction. Time histories with similar frequency contents are applied simultaneously.

These acceleration time histories are used as imposed conditions at the anchorage of the equipment to be tested and are labelled Required Acceleration Time Histories (RATH). If the test facility is not able to adequately apply the RATH, it may apply equivalent signals of similar duration, similar frequency content and whose response spectrum lies above the one of the RATH. To reduce the number of tests, the RATH may be applied in series, one after another, during a single test phase. The time history corresponding to such test is illustrated in Figure 3 as well as a comparison of the resulting spectrum against the RRS.



a) Time histories b) Response spectra

Figure 3. Scaled acceleration time histories and associated response spectra compared to the RRS

Test procedures

When a large number of similar equipment, for example electrical cabinets, must be qualified, the qualification is made on a limited number of pieces which are considered representative of the overall population. This approach is similar to the one described in RCC-E (2019) for the seismic qualification.

Tests are performed either in one direction after the other (mono-axial tests), in three directions at the same time (tri-axial tests) or in two directions at the same time (bi-axial tests). In the seismic qualification standards, it is required that tri-axial tests be performed with full excitation in the three directions simultaneously, bi-axial tests be performed with SRSS combination of the horizontal spectra (or applying a factor $\sqrt{2}$ to the RRS if the excitation is the same in both directions) and mono-axial excitation be performed with SRSS combination of the spectra in the three direction (or factor $\sqrt{3}$). The same procedure can conservatively be applied for testing to APC induced vibrations, but less conservative approaches are also allowable:

- If the building hosting the equipment is directly impacted in one of the APC scenarios, there is always a “strong” direction of response and two “weak” directions of response. It is then reasonable to consider the full excitation in this one “strong” direction of impact only and half of the excitation in the two other directions. The combination coefficients to be applied for bi- and mono-axial test can also be reduced accordingly.

- If the building hosting the equipment is not directly impacted in any of the selected scenarios, the waves travel long distances before reaching it and it is not always possible to identify a “strong” direction. In that case either a detailed analysis shall be carried out to justify case by case coefficients or the conservative combination of the full excitations in all three directions shall be applied.

Extension to the qualification of sub-modules

When sub-modules of equipment are tested instead of full equipment, for example modules that can be located at several elevations within a population of electrical cabinets, specific procedures are set in place: (1) A limited number of cabinets are selected as representative of the overall population in terms of mass, stiffness and dimensions. (2) Transfer functions for these cabinets are determined either experimentally, numerically, or with a combination of both approaches. (3) The RATH are numerically transferred from the cabinet anchorage to each module altitude through these transfer functions. (4) Envelope in-cabinet response spectra are generated enveloping the oscillator response spectra of each time history for all altitudes of all calculated cabinets models. Envelope in-cabinet response spectra are generated for each direction. (5) In the frequency domain above the range of the cabinets’ first frequencies, the envelope response spectra are further broadened of +/- 15 % around each peak. The broadening methodology is similar to the one used for seismic analysis. (6) These envelop and broadened in-cabinet response spectra are defined as the new RRS to be considered for the sub-modules qualification program. Then the same procedure as with RRS on floor level is applied.

EXAMPLE OF APPLICATION: I&C CABINET

Test set up

A fully equipped I&C cabinet was mounted on a 3-axial shaking table and submitted to both earthquake excitation and APC excitation. Some views of the experimental set-up are given in Figure 4. The X direction is along the cabinet width while the Y direction is along the cabinet thickness. The overall mass of the equipped cabinet is 400 kg.

Figure 4. Views of the experimental set-up

For DBE and APC types of excitations, the loads were applied in two steps starting with 100% of the target load (DBE then APC) and then 150% (APC then DBE). The corresponding APC loads in the horizontal directions are illustrated in Figure 6 where the curves 1 to 6 correspond to the load cases LC1 to LC6. The target (100%) maximum floor acceleration was 2g. In the vertical direction, the target was, in this case, higher than the horizontal and set at 3g. According to the methodology developed in the previous paragraphs, 6 RATH were generated to adequately cover the RRS. Excitations were applied in full simultaneously in all three directions, no advantage being taken from the directionality effect in this case.

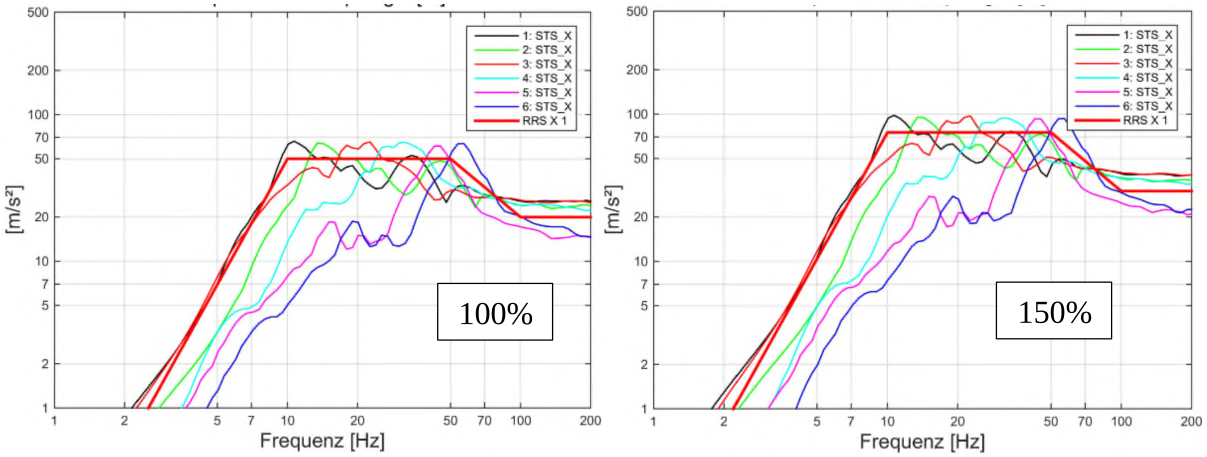


Figure 5. Applied horizontal APC loads – Test Response Spectra for 5% damping

During a sine sweep excitation before the testing, two main horizontal modes of the cabinet were identified at 26 Hz in X direction and 31 Hz in Y direction.

Test results and interpretation

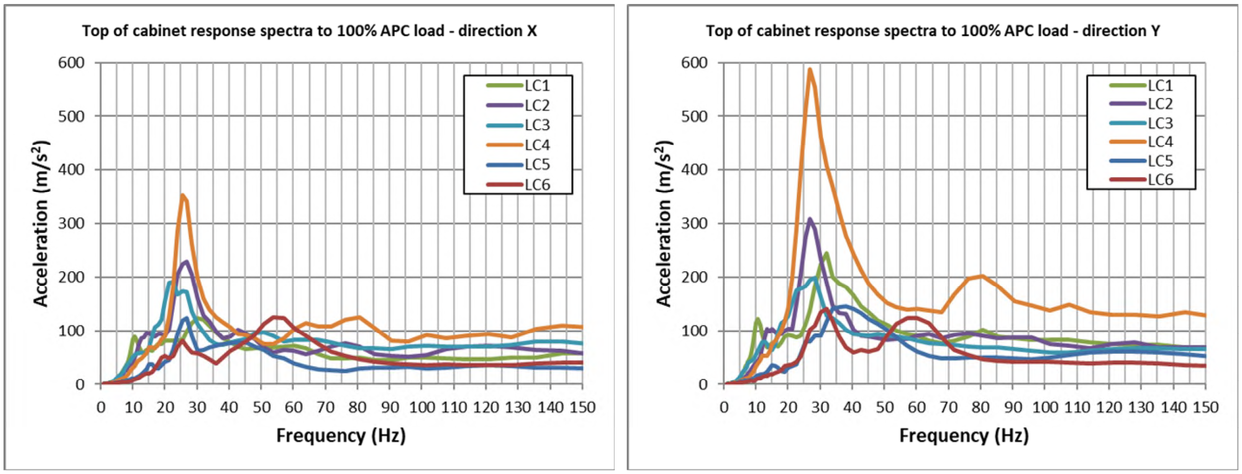
After applying the APC loads, even at 150%, the cabinet structure was fully undamaged, no bolt was found to be loosened and the natural frequencies of the cabinet were not significantly affected. The earthquake loads on the other side, even though having spectral values almost twice lower than the APC in the frequency range of the cabinet natural frequencies, were found to affect the structure. The application of 150% of earthquake load, resulted in the loosening of some bolts, the decrease of the cabinet natural frequencies and a visible increase of its damping. These observations strengthen the fact that APC induced vibrations are actually less damaging than earthquake loads for mechanical structures, even though a comparative numerical spectral analysis might sometimes conclude otherwise.

The cabinet and table APC responses were recorded at several locations including one point at the top of the cabinet, where the cabinet amplification is expected to be maximum. Top of cabinet response spectra were generated for each load case and these spectra are given respectively for the 100% and 150% of APC load in Figure 6 and 7. From these figures, the load case 4 is clearly the one generating the maximum response of the cabinet. For this load case, the peak of the excitation spectra, visible in Figure 5, produces a strong resonance of the cabinet main mode in the Y direction, at a frequency about 27 Hz, resulting in response spectra with amplitude twice larger than for all other load cases.

The predominance of the load case 4 is fully in line with the theory, assuming an almost linear response of the cabinet to the applied excitation. This, the absence of damage and the absence of frequency shift after the test indicate that the cabinet structure mostly remained within its linear range during the APC loading.

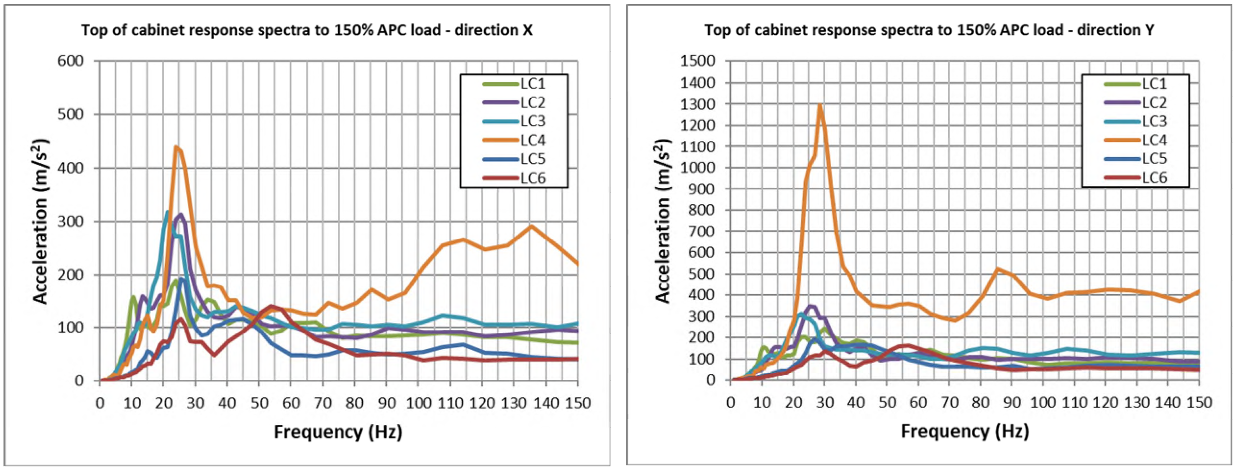
For all but the load case 4, the evolution of the APC loads from 100% to 150% of the target load resulted in a logical and almost linear increase of the cabinet response. This again differs from the observations of seismic response whose increase tend to be less than proportional to the increase of excitation due to the increase of damping induced by damages within the structure.

For the load case 4 only, the increase from 100% to 150% of the APC load resulted almost in a doubling of the response. Besides, impacts were audible during the test at 150% and the response spectra in the X direction shows a pattern typical of impact induced at high frequency (above 100 Hz). It is believed that a threshold of internal acceleration was passed during the test, making impacts occur within the cabinet structure and resulting in a seemingly increased response of the cabinet.



a) X direction b) Y direction

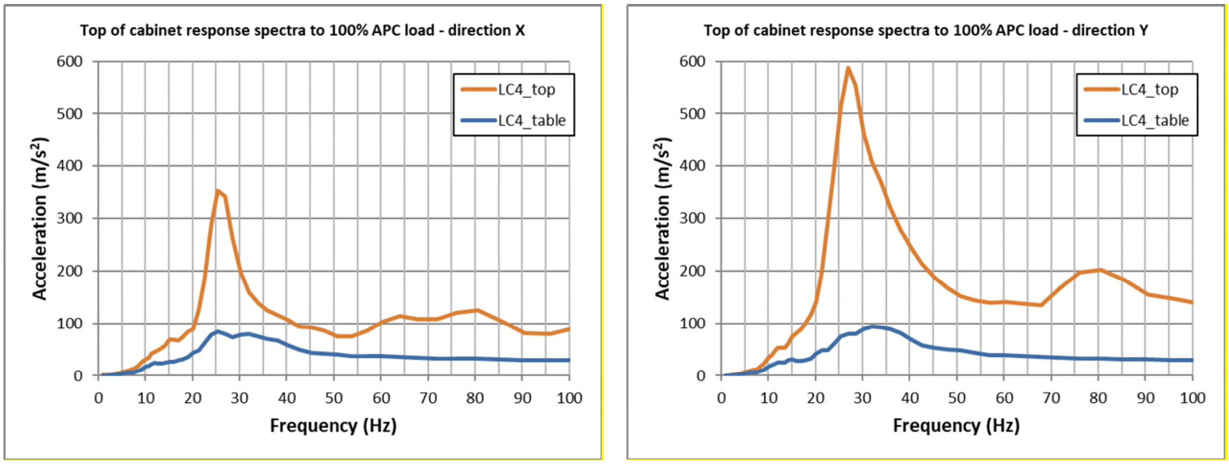
Figure 6. In-cabinet response spectra for 100% of APC loads



a) X direction b) Y direction

Figure 7. In-cabinet response spectra for 150% of APC loads

The significant amplification observed at the cabinet top relative to the excitation at the shaking table level is illustrated in Figure 8 for 100% of the target APC load and load case 4. The possible filtering of APC excitation at the cabinet anchorage onto the floor, documented in Vlaski (2013) and Hervé (2014), seems not to be occurring for this case. It is the opinion of the authors that such filtering is indeed very dependent on the anchorage and supporting characteristics of the cabinet. In the experiment described here, the cabinet as well as its anchorages can be defined as stiff and robust when submitted to realistic APC loads as applied with the methodology proposed in this paper. They do not experience any yield or sliding during the application of APC excitation. On the contrary, both structure and fixations exhibit a very non-linear and dissipative behaviour when submitted to 150% of earthquake loads. This highlights the cumulative nature of the damage inflicted by an earthquake to a cabinet like bolted structure, which simply does not exist with realistic APC loads.



a) X direction b) Y direction

Figure 8. Comparison of table and cabinet top response spectra for 100% of APC load, load case 4

Generation of APC qualification loads for the sub-modules

Based on the experiment presented before, envelop in-cabinet response spectra covering the cabinet response to all 6 APC excitation load cases are generated. These envelop in-cabinet response spectra can be completed with the results of tests on other configurations of cabinets (same external structure with other internal components) or, more efficiently, with the results of calculations based on a finite element model of the cabinet structure that is checked or calibrated using the experimental results. The resulting overall envelop spectra becomes the new target APC qualification spectra for the cabinet sub-modules.

Once the sub-modules qualification spectra are known, the same testing methodology is applied. A selection of time histories extracted either directly from the test or from the additional finite element calculations are selected so that, together, their spectra envelop the sub-modules qualification spectra. The sub-modules are then tested on shaking table with applying the time histories one after the other and combining the different excitation directions.

CONCLUSION

A new methodology was developed for qualifying I&C and electrical equipment to APC induced vibrations. The methodology remains in line with the principles underlying the seismic qualification in design codes and standards but adapts it to the specificities of APC induced vibrations that are: its short duration, its higher frequency content, and its strong directionality effect. The method consists in the definition of sets of required acceleration time histories (RATH) based on time histories effectively calculated during the building response analysis to APC. The selection is made so that the APC required response spectrum is enveloped by the response spectra of these RATH taken together. The directionality effect is accounted for by applying reduction coefficients to the loading in certain directions during the test, depending on the type of test and of the host building configuration: the directionality effect is stronger in a building impacted directly.

The methodology was applied for the test of a fully equipped I&C cabinet and the outcome of the test confirmed the different behaviour of the cabinet under APC and earthquake loads, thereby justifying the need for addressing them separately. Especially, when increasing the excitation level to 150% of the target, the cabinet frame and its fixation to the shaking table were significantly less affected by the APC loads than by the earthquake loads. The cabinet was undamaged and remained practically linear under 150% of the APC loads while experiencing significant change of behaviour when submitted to 150% of the earthquake load. This was observed even though the spectral acceleration of the APC load at the resonant frequency of the cabinet was higher than the one of the earthquake loads. The cumulative effect of earthquake induced damage, due to the longer duration of this type of excitation compared to the APC, is clearly illustrated here.

As a consequence of the cabinet structure remaining mostly linear, the same experiment also showed that the APC high frequency content can be passed through the cabinet structure to the internal sub-modules and is not filtered out by the anchoring or by the cabinet structure as it was observed on other pieces of equipment (see Vlaski 2013, Hervé 2014 and Gupta 2021). With 150% of the most severe APC load case, it was even observed that the appearance of impact non-linearities within the cabinet itself was contributing to an apparent increase of the in-cabinet response spectra in the high frequency range. The occurrence of this type of non-linearities is very dependent on the cabinet sub-module placement and design. Beside it is not a design objective that the cabinet remains linear under APC loads.

Because of the mostly linear response of the particular cabinet tested, the required qualification spectra for the sub-modules remain high. The application of the same testing methodology for the sub-modules as for the cabinet is then highly recommended. In particular, the use of time histories of realistic duration and frequency content, extracted from the tests results and then slightly modified to generate a set of load cases that, together, envelop the target qualification spectra, is key to a successful qualification.

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