Probabilistic Assessment of NPP Building Vibrations Caused by Aircraft Impact

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ABSTRACT

An accidental aircraft impact on the NPP building causes its forced vibrations and dynamic loads on the equipment located within it. Their intensity depends on the aircraft class, mass and velocity, load vector direction in space, and also on the distance between the place of impact and the location point of the equipment item under consideration. All these parameters are random ones, therefore dynamic loads on the equipment are also random quantities.

The methodology of floor response spectra (FRS) development with various probabilities of exceedence is described in the report. All random parameters mentioned above are considered. Examples of FRS calculations are given. They show that FRS ensuring even very small probability of exceedence is significantly lower than FRS for the most unfavorable case.

The methodology can be used both when designing new NPPs, and when the analysing the safety of the existing ones.

1. INTRODUCTION

The analysis of the NPP building forced vibrations caused by aircraft impact is carried out to obtain inertial loads transmitted on the processing equipment to check its strength and serviceability. When performing this check the dynamic influence is commonly set by means of floor response spectra (FRS), calculated for the place of the equipment unit location or on the building level. FRS are designated below as $S(f,\zeta)$, where f, Hz is frequency and ζ is critical damping. FRS is known to be the dependence of the absolute values of maximum forced vibration accelerations of the linear damped oscillator on its natural frequency f and damping ζ, when the disturbed motion is caused by a building point vibrations.

The forced vibrations intensity of a considered point of a building, and consequently, FRS shape depends on the aircraft class, mass and velocity, direction and place of application of aircraft impact load, as well as on the distance between the building point under consideration and the place of impact. Accelerations of building structures and FRS acceleration values can appear to be very severe, especially if the building point where FRS is calculated is close to the place of impact.

It is common today to design NPP following the assumption, that the worst variant of external event is realized. This means, that the impact of the aircraft with maximal mass and speed should be considered, which is applied to the most unfavorable point of a building and at the most dangerous angle to the structure surface. This principle being followed strictly, the analysis of the equipment should be carried out with the use of the envelope of FRS, which correspond to impacts of the aircraft on all points of a building. As follows from the above, design accelerations can thus appear very severe.

Besides, the accelerations caused by an aircraft impact have another unpleasant feature. This disturbance contains higher frequency harmonics, than an earthquake, which should now be accounted for anyone NPP. Because of that maximal acceleration values at aircraft impact are shifted to a more high-frequency area, than with the seismic load. For this reason if both an earthquake and an aircraft impact should be taken into account, some problems arise when designing NPP equipment, as it is difficult to tune its natural frequencies out of the frequency range, where maximum accelerations are reached.

But in reality an aircraft fall on the NPP is a very rare event. Besides all the parameters mentioned above, on which the acceleration of a building structure depends, are casual, and the probability of simultaneous realization of their values, causing maximum accelerations transmitted on the equipment, is very small.

The approximated methodology of the FRS development caused by an aircraft impact with the required probability of acceleration exceedence is described below. It allows estimating real design acceleration values ensuring the required NPP safety level. It can be used both when designing new NPPs, and when analyzing the safety of the existing ones.

2. PROBABILISTIC PROCEDURE OF FRS DEVELOPMENT

2.1. Considered Random Parameters

FRS is developed taking into consideration the following random parameters: aircraft fall recurrence; load vector direction in space; the impact load value depending on the aircraft class, mass m and velocity v; distance from a place of impact up to the considered point of the building. In principle, their probability characteristics (except the distance) should be determined by analyzing the airspace situation in the vicinity of the NPP. To explain the described methodology, these characteristics are specified on the basis of the world statistics and technical publication data.

The impact of the aircraft Phantom RF-4E is considered. The aircraft fall recurrence is taken as that in Germany, namely: $\mu = 10^{-6}$ 1/year on area $A_0 = 10^4$ m^2. Probabilitiy distributions of mass, velocity and direction of the aircraft fall are assumed the same as in the report, Ref. [1], published in Transactions of the present conference.

2.2. FRS Probability Distribution

When NPP building vibrations are calculated, a linear mathematical model of the building is used. Therefore the building structure accelerations are proportional to the maximum value of the aircraft impact force. If the impact is applied at an angle to the structure surface normal, it is the normal component of the load alone that is taken into account for the sake of simplicity in the described methodology. This assumption is partly justified by the fact that if the angle between normal and impact force is small, the tangential component is small too, and if it happens to be large, the sliding and ricochetting of the aircraft are possible, which decrease the load.

Let the casual event "impact of the aircraft on the j-th point of a building" be designated as $\boldsymbol{B}_j$. If the surface area attributed to this point (to a FEM grid node) is A_j, the probability of event $\boldsymbol{B}_j$ is calculated by the formula developed in the report Ref. [1], and is equal to

$$P(\boldsymbol{B}_j) = 10^{-4} A_j \cdot \exp\left(-10^{-4} A\right), \tag{1}$$

where A is the total area of outer building surface accessible to an aircraft impact.

Assume that the normal to the building structure surface in the point of the aircraft impact is inclined at an angle φ to the vertical. If the impact coincides with the normal, and the aircraft has the maximum mass and velocity, the normal component of the load is $R_{max}(t)$. The corresponding FRS in the considered point of a building (i.e. in the place of fastening the equipment to be check) is designated as $S^*_j(f)$. For brevity sake the dependence of FRS on ζ is not specified here, as the procedure of probabilistic development of FRS at any damping is the same.

If the aircraft mass and velocity are not maximum, and the impact is applied at an angle γ to the normal, then the normal component of the load is equal to

$$R_n(t) = cR_{\max}(t), \tag{2}$$

where

$$c = k_\gamma k_{mv}; \tag{3}$$

$k_\gamma = \cos\gamma$; factor k_{mv} is the ratio of the maximum load value corresponding to the given aircraft mass m and velocity v, to the maximum load corresponding to the greatest m and v. Impact load was calculated by Riera's formula, Ref. [2], and thus $0.17 \leq k_{mv} \leq 1$ was obtained.

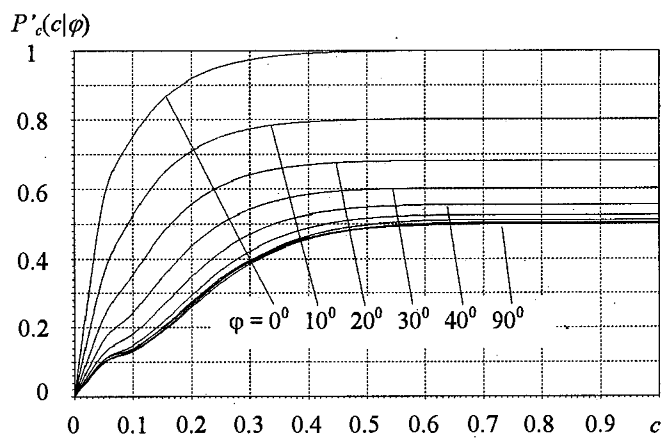

Fig. 1. Function $P'_c(c|\varphi)$

Factor c is a random variable. Its cumulative distribution function is

$$P_c(c|\varphi) = \begin{matrix} P'_c(c|\varphi) & \text{if } c \leq 1; \\ 1 & \text{f } c > 1, \end{matrix} \tag{4}$$

Function $P'_c(c|\varphi)$ is depicted in the fig. 1. The density function $p_c(c|\varphi)$ can be obtained by differentiation of $P_c(c|\varphi)$.

On account of the problem linearity, if the impact is applied on the j-th point, and the aircraft mass and velocity, as well as the load angle to the normal are arbitrary, then FRS equals (fig. 2):

$$S_j(f) = c\, S^*_j(f), \tag{5}$$

where $S^*_j(f)$ is the FRS corresponding to an impact along the normal and maximum mass and velocity of the aircraft.

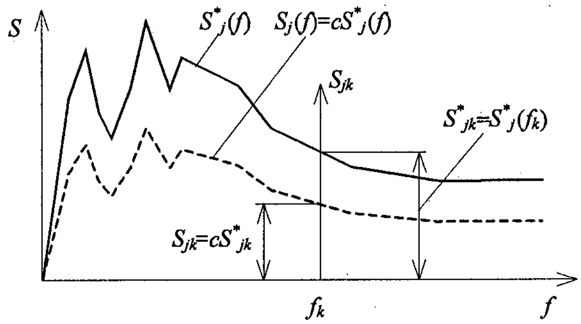

Fig. 2. FRS dependence on factor c

Consider FRS acceleration values at any oscillator frequency f_k. Its maximal value $S^*_j(f_k)$ is, for brevity, denoted S^*_{jk}. At any factor c the FRS value is $S_{jk} = cS^*_{jk}$. As the multiplier c is a random variable, S_{jk} is a random variable, too. As it corresponds to an impact on the j-th point of the building (casual event $\boldsymbol{B}_j$), its conditional density function is equal to

$$p_s\left(S_{jk}\middle|\boldsymbol{B}_j\right) = \frac{1}{S^*_{jk}}\, p_c\left(\frac{S_{jk}}{S^*_{jk}}\right). \tag{6}$$

The cumulative distribution function equals:

$$P_s\left(S_{jk}\middle|\boldsymbol{B}_j\right) = \frac{1}{S^*_{jk}} \int_0^{S_{jk}} p_c\left(\frac{S_{jk}}{S^*_{jk}}\right) dS_{jk} = \int_0^{cS^*_{jk}} p_c(c)\,dc = P_c\left(cS^*_{jk}\middle|\varphi_j\right), \tag{7}$$

where cumulative distribution function $P_c(cS^*_{jk}|\varphi_j)$ is calculated by Eq. (4). Thus, the conditional probability of non-exceedence of value $S_{jk}=cS^*_{jk}$ is equal to the probability of non-exceedence of value $c_{jk}=S_{jk}/S^*_{jk}$.

The total probability of S_{jk} non-exceedence equals

$$P_s\left(S_{jk}\right) = P_s\left(S_{jk}\middle|\boldsymbol{B}_j\right)\cdot P\left(\boldsymbol{B}_j\right) = P_c\left(c_{jk}\middle|\varphi_j\right)\cdot P\left(\boldsymbol{B}_j\right). \tag{8}$$

The density functions of FRS acceleration values is similarly determined at other oscillator frequencies.

If the aircraft impact is appeared to another, the n-th point of the building (casual event $\boldsymbol{B}_n$), the probability $P_s(S_{nk})$ of non-exceedence of FRS, both at frequency f_k and at all other oscillator natural frequencies can be calculated in the way described above.

As the casual events $\boldsymbol{B}_j$ and $\boldsymbol{B}_n$ (i.e. impacts in different points of a building) are independent ones, density function of FRS value at any oscillator frequency is equal to the sum of probability densities for each of the mentioned events (fig. 3). This procedure having been repeated for impacts on all m points of the outside building surface, the probability densities $p_s(S)$ of FRS acceleration values at all oscillator frequencies in all building points of interest are obtained. The cumulative distribution function of FRS value S_k at frequency f_k is equal to

$$P_s\left(S_k\right) = \sum_{j=1}^{m} P_c\left(c_{jk}\middle|\varphi_j\right)\cdot P\left(\boldsymbol{B}_j\right). \tag{9}$$

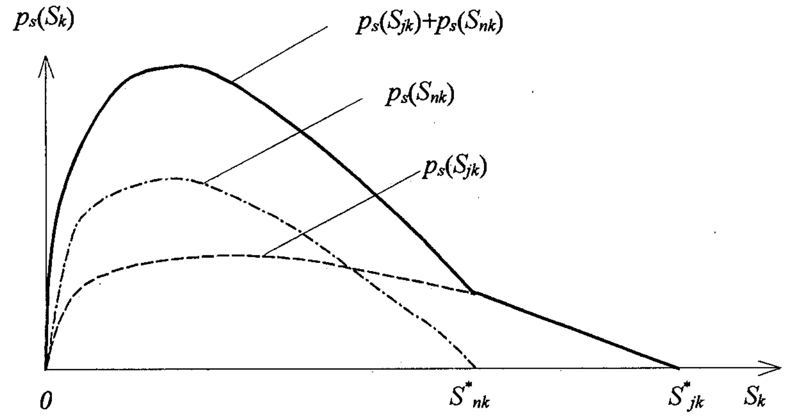

Fig. 3. Density function of FRS acceleration value at frequency f_k with consideration of the impacts in the j-th and the n-th building points

As was mentioned in item 3.2, it is a common practice to estimate the probability of NPP structures and equipment failure in the term of 1 year. At the aircraft fall recurrence as specified in item 2.1, the probability of FRS value non-exceedence should for this purpose be multiplied by 10^{-6}, i.e. it equals

$$\overline{P}_{exc}(S_k) = 10^{-6} P_c(S_k). \tag{10}$$

The probability of its exceedence during this time is

$$P_{exc}(S_k) = 10^{-6}[1 - P_c(S_k)]. \tag{11}$$

With Eq. (11) FRS with the given probabilities of acceleration value exceedence can be developed.

2.3. Design Probability of FRS Acceleration Values Exceedence

When the probabilistic estimation of the equipment reliability is carried out, the criterion of its serviceability preservation looks like

$$P_f \leq [P], \tag{12}$$

where P_f is the probability of failure within one year, which usually means the failure to meet the requirements related to maintenance of radilogical and nuclear safety; $[P]$ - admitted probability of failure.

The question as to what FRS non-exceedence probability value for an equipment unit under consideration should be chosen to fulfill the condition (12) is to be decided on the basis of the analysis of systems failure probability with consideration of the series and parallel arrangement of components. For this purpose a failure tree should be constructed and analysed. The complete decision of this problem lays outside the present report. Only an approximated estimation of the influence of the probability factors on the design FRS is done below on the basis of some simplifying assumptions.

Assume that the exceedence of FRS calculated for the point of installation of the considered equipment unit is equivalent to the failure of the latter. This assumption provides the margin of reliability, as the response-spectrum method in itself provides large margins, in particular because the possible non-linear behavior of the equipment can not be strictly taken into account. It is especially true when an aircraft impact is considered, as this method does not take into consideration the high-frequency and momentary character of the load. With the assumption the following equation results from Eq. (11):

$$P_f = 10^{-6}[1 - P_c(S_k)]. \tag{13}$$

Assume, too, that the failure of a system or an equipment unit of interest leads to the failure of the whole NPP. This assumption also gives a large reliability reserve. In the IAEA Safety Guide, Ref. [2] the value 10^{-7} is given as a limit of the probability of occurrence per annum of events eventually leading to radiological consequences. This value as the admitted probability of failure for the considered equipment unit being accepted, i.e.

$$[P] = 10^{-7}\ \text{1/year}, \tag{14}$$

then with Eqs. (11) - (13) it is follows that

$$10^{-6}\left[1 - P_c(S_k)\right] \le 10^{-7}, \tag{15}$$

whence

$$P_s(S_k) \ge 0.9. \tag{16}$$

3. EXAMPLES

To show the advantages which probabilistic development of FRS can give, FRS calculations for a reactor building were made. Its FEM model is represented in fig. 4. The building rests on a medium soil foundation. The impact of the aircraft Phantom RF-4E was considered.

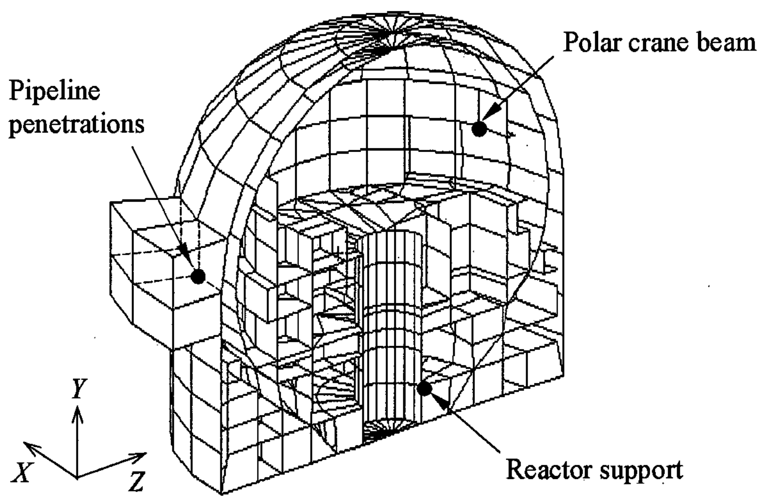

Fig. 4. Reactor building FEM model

To do probabilistic processing, FRS at impacts in all containment FEM mesh nodes were calculated. Probabilistic FRS were developed in the following three characteristic points: the reactor support; the polar crane beam; pipeline penetrations in the reinforced concrete containment (fig. 4).

The results of aircraft FRS calculations are shown in fig. 5. For comparison, FRS corresponding to the earthquakes with the peak ground accelerations (PGA) $0.1g$ and $0.2g$ are also given there. For brevity sake only the horizontal components Z at critical damping 2% are depicted. The results of the calculations of other FRS components and for other damping factors are similar.

In the figures envelopes over FRS corresponding to the aircraft impacts on all containment points are given. They represent the worst variant of loading. They are seen to surpass the seismic FRS in the range of frequencies higher than 3÷5 Hz. Thus at the place of the arrangement of pipeline penetrations, which is close to the points of the impact of the aircraft, the maximum acceleration surpasses $30g$.

The probability aircraft FRS satisfying the condition Eq. (16) are also given in the pictures. Even at the point of the arrangement of pipeline penetrations the aircraft FRS is seen not to surpass the seismic FRS corresponding to an earthquake with PGA=$0.2g$. On the reactor support, located in the center of a building, the aircraft FRS is below the seismic one for PGA=$0.1g$. This means, that as such an earthquake should be necessarily accounted in the NPP project, the additional check of the reactor on aircraft impact loads may not be carried out.

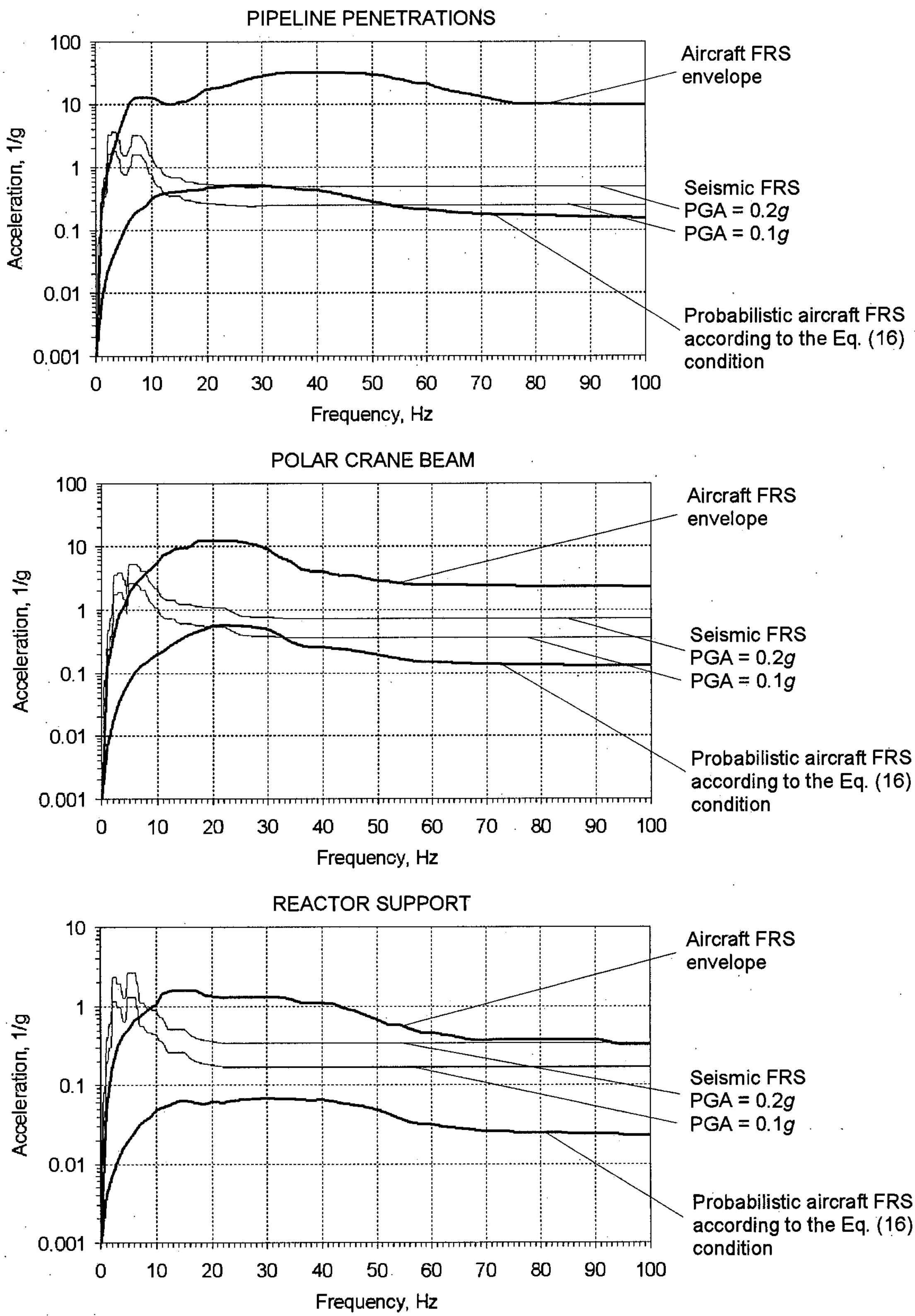

Fig. 5. Floor response spectra
Horizontal components Z, 2% critical damping

CONCLUSION

Dynamic loads transmitted on the equipment at an aircraft impact on a NPP building can be very severe. The probabilistic methodology of FRS development described in the report allows to take quantitatively into account the rarity of this event and the randomness of the parameters characterizing it. The given examples of the calculations show, that in view of these circumstances the aircraft FRS can be decreased to the level of seismic ones corresponding to the earthquakes with the peak ground accelerations from $0.1g$ up to $0.2g$. At some points of the building the aircraft FRS may appear to be below the seismic one for PGA=$0.1g$. As such earthquake has to be necessarily taken into account when designing NPPs, the equipment located at these points may not be checked at all for an aircraft impact.

REFERENCES

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2. Riera J.D., "On the Stress Analysis of Structures Subjected to Aircraft Impact Forces," *Nuclear Engineering and Design*, Vol. 8, 1968, pp. 415-426.