Analysis of dynamic response of nuclear power plant buildings under aircraft impacts on reactor containments

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ABSTRACT

The paper reports the results of calculation analysis of the dynamic behavior of engineering structures of a nuclear power plant reactor compartment under an impact of a crashing aircraft against a reactor containment. Accelerograms and response spectra for aircraft impact loadings applied in various directions and zones of a building are evaluated. Probability estimate of the acceleration values obtained is given. It is shown that in some cases inertia loads on equipment caused by aircraft impacts may prove to be higher than at MDE.

INTRODUCTION

In designing nuclear power plant buildings it is common practice to determine inertia loads on equipment by their response spectra. Such spectra are analysed for some dynamic loading within a given set of points of a structure scheme. Of all the loadings of this type, those concerned with earthquakes or crashing aircraft impacts on a reactor containment seem to be the most dangerous ones. An aircraft impact is a very concentrated high-frequency load. For this reason, it calls for an in-depth analysis of a three-dimensional behavior of a structure and the use of sufficiently detailed design schemes.

In the given work, a nuclear power plant building is schematized as a composite shell of revolution.

A computer program system ASTAN, developed by the B.E.Vedeneev VNII& researchers for computers EC
and IBM PC/AT, is employed. The system is meant for calculating sophisticated branched axisymmetric thin-walled structures under static and dynamic loadings in a linear-elastic formulation [1]. The design scheme proposed may encompass up to 1000 nodes in a radial section. The algorithm is based on the Fourier series expansion in terms of an angular (in plan) coordinate, the superelement method and the equations of thin shells of revolution. The dynamic problems are solved by series expansion in terms of natural modes of vibrations [2]. A special recurrence formula is used for integration of the expanded equations of motion [3]. The program system ASTAN is capable to perform calculations for a whole set of loads at a time. As a result of the analysis, node accelerograms and response spectra for the loads arbitrarily varying with time and coordinates are evaluated. The capability of the system affording the use of the schemes with a large number of degrees of freedom permits of including higher modes of vibrations at frequencies up to 50–60 Hz.

To examine the dynamic behavior of engineering structures of a nuclear power plant reactor compartment under an aircraft impact, a design scheme of a radial section such as that of Fig. 1, was adopted. A scheme comprises 82 fragments of plates, cylindrical and spherical shells rigidly connected in 57 joint nodes. A footing slab rests on an elastic foundation of the Winkler type. The fragments of the structure are made of the materials of 5 types having various elastic and inertia characteristics. Each fragment is represented as a superelement divided into 10 quasi-onedimensional finite elements of equal length.

The trend of variation of impact loads with time (Fig. 2) is adopted following the IAEA recommendations for the military aeroplane "Phantom RF-4E22". The given type of impact loading is specified for an aeroplane weight of 20 tonnes and a velocity of 250 m/s. The area of a contact zone is 14 m² and the duration of an impact is 70 ms. The 0.3 s observation interval was selected for examining the dynamic behavior of the structure. Node accelerograms were evaluated with a time step of 2.5 ms in three mutually orthogonal directions for 23 observation points (the numbers of points are given in Fig.1). The number of terms of the Fourier series expansion was taken to be equal to 20. The results of the test problems solution have indicated that this number gives a fairly good accuracy in evaluation of the node accelerograms. The number of natural modes of vibrations involved was selected for each of the solution harmonic components individually and deter-
mined by the values of natural frequencies in the range of up to 50 Hz. The number of modes included have totaled in this case more than 400. For each of the modes, the damping in the structure was assumed to be equal to 6 % of the critical one. Fig. 3 shows, as an illustration, one of the node accelerograms obtained. In the analysis of the response spectra, the oscillator frequencies were selected in the range up to 30 Hz with damping constituting 0.5, 3 and 7 %.

In some publications [4,5,6], the problem of determining the dynamic characteristics of nuclear power plant buildings under an aircraft impact is solved in a non-linear formulation with account for an inelastic behavior of the material within an impact zone. In the centre of the area of an impact, the inclusion of the physical nonlinearity leads to a several-fold increase in accelerations, exhibiting but locally.

At a distance of 11 to 14 m from the contact zone, the accelerograms obtained in a linear formulation differ from those in a non-linear formulation by a few per cents only, while at a greater distance they are practically identical. Hence, a linear formulation seems to be quite reasonable.

The parameters of an aircraft impact against a reactor containment are of a probabilistic nature. One of the most important problems of the structure response analysis for the loads of the above type is that of evaluating the output characteristics as random values. The present study offers a simplified procedure for deducing the probability distribution laws for response spectra.

The important factors that have a direct bearing on the values of accelerations of structure elements and which are not specified in the IAEA recommendations are the location and the direction of impact loading. Acceleration $\alpha$ in response spectra may be treated as a continuous random value which takes on certain values as a result of a specifically-oriented crash of an aircraft onto a building. An endless set of impacts is substituted by a finite one, comprising $N$ variants. These variants are arbitrarily assumed as being equiprobable. Then each oscillator with its characteristic damping and frequency has $N$ values of maximum accelerations $\alpha_i$ ($i = 1, \ldots, N$). These values are arranged in an increasing order of magnitude ($\alpha_1 < \ldots < \alpha_{L} < \ldots < \alpha_N$).

Acceleration $\alpha_N$ is taken as the maximum possible value. In this case (provided that the impact is an actual event) the probability that the random value of $\alpha$ will find itself in either of the intervals...
The concept of probability introduced for accelerations is to be treated as the probability of their non-exceedance of the values obtained for a particular variant of an impact. Spectra with probability $\rho_0 = \frac{1}{n}$ ($i = 1, \ldots, N$) are obtained graphically by way of successive joining of points corresponding to the values of $a_i$ and having the same number of $i$ for all of the oscillators analysed.

As the most hazardous loadings, considered were 10 variants of impacts against the top of a dome in the zone of its contact with a cylindrical portion of the containment and in the upper portion of the exterior structures. The direction of impacts was assumed normal to the containment and under an angle of 45° to the normal in the vertical and horizontal radial planes. The results of calculations performed have indicated that the accelerations of the equipment elements decrease sharply as the distance of the observation point from the zone of the impact load increases. This is particularly typical for horizontal accelerations under normal impacts on a cylindrical portion of the containment. A vertical impact against the dome top produces increased accelerations not only in the upper, but also in the lower floors of a building. The vibrations in the elements located in the interior of the containment attenuate more rapidly, while within the exterior structures much slower. For comparatively flexible structure elements, accelerations are found to reach their peak values in response spectra at frequencies of 10 to 16 Hz, for rigid elements at 23 to 27 Hz. In proximity to the area of an impact, these values may be as great as $10 \, g$ and higher. At the lower floors of the building (el. 10.0 m) the horizontal accelerations in response spectra are found to be not higher than $(1.0-1.5) \, g$, whilst the vertical ones no greater than $(4.0-5.0) \, g$.

When determining design inertia loads on equipment, it should be born in mind that the probability of an aircraft crash in the manner, that might lead to maximum accelerations, is extremely low. Therefore, it is reasonable to use spectra with the probability of $\rho_0 < 1$, for instance, $\rho_0 = 0.9$ or $\rho_0 = 0.5$ depending on the degree of importance of a particular element of the equipment. Such an approach allows to prove an appreciable reduction in inertia loads. Fig.4 shows aircraft spectra of horizontal accelerations with various probabilities of $\rho_0$ for the building scheme point 1 (Fig.1). In the same
figure, for comparison, is displayed the response spectrum for a maximum design earthquake (MDE) given by an ensemble of real accelerograms. The seismic spectrum is obtained from the computer program "RESPECT" [3], wherein a building is schematized as a vertical console bar of moderate thickness. In Table given below, a correlation is made between the maximum accelerations in the aircraft spectra with probabilities 1.0 and 0.5 at different floors of the building and the seismic accelerations obtained for corresponding values of oscillator frequencies. Selecting the spectra with $\rho_0 = 0.5$, as the design ones, may prove reduction of inertia loads by 2 to 5 times or more. In this case, the aircraft accelerations at an elevation of below 27.0 m are found to be not higher than the seismic ones in the vast majority of cases. An appreciable excess of accelerations over the MDE level due to an aircraft impact is characteristic for the upper portion of the building. However, these results can also be thought of as being too high, that is accounted for, specifically, by the fact that the observation points are being selected in the same radial section where the load is applied.

Table

<table>
<thead>
<tr>
<th>Node number</th>
<th>$h, m$</th>
<th>$\alpha_x$</th>
<th>$a_{u}^{\text{max}}$</th>
<th>$\alpha_z$</th>
<th>$a_{w}^{\text{max}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>$\rho_0 = 1.0$</td>
<td>$\rho_0 = 0.5$</td>
<td>$\rho_0 = 1.0$</td>
</tr>
<tr>
<td>1</td>
<td>43.5</td>
<td>1.95</td>
<td>11.7</td>
<td>5.2</td>
<td>1.5</td>
</tr>
<tr>
<td>3</td>
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<td>1.7</td>
<td>4.4</td>
<td>2.1</td>
<td>0.92</td>
</tr>
<tr>
<td>5</td>
<td>27.0</td>
<td>1.45</td>
<td>1.6</td>
<td>1.0</td>
<td>0.9</td>
</tr>
<tr>
<td>7</td>
<td>27.0</td>
<td>1.45</td>
<td>1.5</td>
<td>1.2</td>
<td>0.9</td>
</tr>
<tr>
<td>9</td>
<td>21.0</td>
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<td>1.3</td>
<td>1.1</td>
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<tr>
<td>11</td>
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<td>1.0</td>
<td>1.3</td>
<td>0.81</td>
<td>0.84</td>
</tr>
<tr>
<td>13</td>
<td>14.1</td>
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<td>1.6</td>
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</tr>
<tr>
<td>15</td>
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<td>1.5</td>
<td>0.55</td>
<td>0.82</td>
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<tr>
<td>17</td>
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<td>0.68</td>
<td>0.31</td>
<td>0.82</td>
</tr>
<tr>
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<tr>
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</tr>
<tr>
<td>23</td>
<td>-4.95</td>
<td>0.95</td>
<td>0.57</td>
<td>0.38</td>
<td>0.63</td>
</tr>
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</table>
Note: $a_{u_{\text{max}}}$, $a_{w_{\text{max}}}$ are the horizontal and vertical components of maximum accelerations under an aircraft impact, respectively; $a_x$ and $a_z$ are the horizontal and vertical components of seismic accelerations; $h$ is the elevation of the building scheme node.

Related studies have been carried out for the reactor compartment structure of a heat supply nuclear power plant. The integration time was increased to 0.8 s, thereby enabling more reliable results to be obtained for the structure points, far removed from the impact area. The response spectra were being analysed for the oscillators, having frequencies up to 60 Hz. Varying an angular (in plan) coordinate of an impact point resulted in an added reduction of accelerations. The relationship between the structural details of reactor compartments and the values of the equipment elements accelerations was also revealed. Specifically, the lower portion of the structure has greater rigidity. In this zone the response spectra have the characteristic local peaks in the frequency range of 54 to 58 Hz.

CONCLUSION

As to the problem of including additionally the inertia loads caused by aircraft crash in the design of nuclear power plant equipment, being analysed for seismic effects, there is no consensus of opinion among researchers. Some authors conceive that on account of differences in duration and spectral content of earthquake- and aircraft-induced vibrations, a direct comparison of corresponding accelerograms and response spectra is incapable to give an adequate knowledge of the relative hazard of these effects. In the analysis for these loads different strength properties of materials and failure criteria for a structure should be used. Nevertheless, in designing some nuclear power plants, particularly those for heat supply, the problems of ensuring reliability of equipment with loads of the type of an aircraft crash included should receive considerable attention. The problem requires further theoretical studies and calculation analyses, predominantly with the employment of probability methods.
Figure 1: Design scheme of a nuclear power plant building.

Figure 2: The trend of variation of an impact load with time.

Figure 3: Accelerogram in point 1 of the building scheme (vertical component) under normal impact of an aircraft onto a dome top.
Figure 4: Acceleration spectra with a given probability $\rho_0$ in point 1 of the building scheme (horizontal component); 1 - under an aircraft impact, 2 - under a seismic effect.

REFERENCES


