RESULTS OF AN ANALYSIS OF FIELD STUDIES OF THE INTRINSIC DYNAMIC CHARACTERISTICS IMPORTANT FOR THE SAFETY OF NUCLEAR POWER PLANT EQUIPMENT

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A classification of the equipment important for the safety of nuclear power plants is proposed in terms of its dynamic behavior under seismic loading. An extended bank of data from dynamic tests over the entire range of thermal and mechanical equipment in generating units with VVER-1000 and RBMK-1000 reactors is analyzed. Results are presented from a study of the statistical behavior of the distribution of vibrational frequencies and damping decrements with the "small perturbation" factor that affects the measured damping decrements taken into account. A need to adjust the regulatory specifications for choosing the values of the damping decrements with specified inertial loads on equipment owing to seismic effects during design calculations is identified. Minimum values of the decrements are determined and proposed for all types of equipment as functions of the directions and natural vibration frequencies of the dynamic interactions to be adopted as conservative standard values in the absence of actual experimental data in the course of design studies of seismic resistance.

Keywords: nuclear power plant; equipment; seismic stability; dynamic characteristics; natural frequencies; damping decrements

Work on the design and experimental evaluation of seismic resistance and stability with respect to external effects by equipment that is important for the safe operation of nuclear power plants with a determination of its intrinsic dynamic characteristics under actual conditions of installation and piping disassembly and assembly [1] is recommended in the IAEA standards [2] and regulated by the Russian federal standards documents [3] and specialized standards and instruction documentation [4 – 6] for installation of new power generating units in nuclear power plants and extending the operating lifetime of these plants. The resulting experimental data is of practical importance for more precise determination of the inertial loads on equipment from resonant external interactions (seismic, air shocks, airplane crashes, etc.).

In connection with the rapid installation of new nuclear power plants in Russia and abroad in accordance with Russian designs, with extensions of the operating lifetimes of a number of operating power generating units, and with the corresponding increase in the volume of design and experimental work on seismic resistance and stability with respect to external interactions of equipment important for the safe operation of nuclear power plants, the analysis and systematization of these data from dynamic tests is particularly important.

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The greatest interest in analyzing the data from dynamic tests is to identify statistical behavior intrinsic to the natural modes of the equipment in its actual state, i.e., under actual conditions of installation, disassembly, or reassembly in a nuclear power plant. These data can also provide an experimental justification for and facilitate improvements in the Russian standards documentation [7, 8] for the values of the relative logarithmic damping decrements (referred to as damping decrements) employed in design determinations of the stability of nuclear power plant equipment with respect to external interactions [9].

In 2008 a general statistical analysis was carried out of test data on 416 pieces of equipment at units Nos. 1 – 3 at the Leningrad Nuclear Power Plant, No. 3 at the Kalinin Nuclear Power Plant, and No. 1 at the Rostov Nuclear Power Plant, as well as of test data on various electrical engineering equipment at manufacturers' plants [10].

The character of the "small perturbation" factor and its importance in the accuracy of a determination of the damping decrement was emphasized and studied for excitation of low amplitude vibrations at 1 – 2 orders of magnitude lower than actual seismic interactions; this was done to meet the requirement that equipment should not be damaged during the direct tests at a nuclear power plant. A special model experiment showed that the decrements increased by no more than

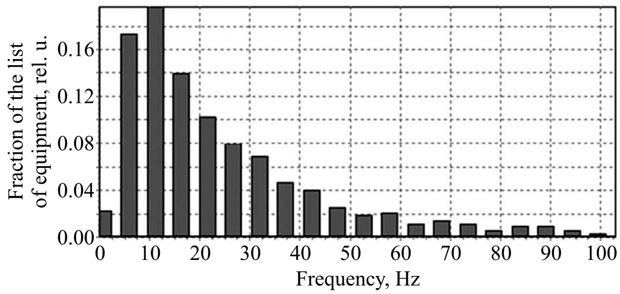

Fig. 1. Distribution of the natural frequencies in all directions over the range 0 – 100 Hz.

a factor of 1.5 – 2 on going from small to large vibrational perturbations.

For the purpose of a statistical analysis of the accumulated data, all the equipment was classified in groups according to their dynamic behavior under external resonance interactions. Each group included several different types of similar equipment. The proposed classification (Table 1) includes the major types of equipment most widely used in nuclear power plants and is made up of 12 groups.

Here we present the results of an analysis of data that we have accumulated on startup and operating power generating units at nuclear power plants (Nos. 1 – 4 at the Leningrad Nuclear Power Plant, No. 2 at the Rostov Nuclear Power Plant, and No. 4 at the Kalinin Nuclear Power Plant) from 2005 to the present. This extensive bank of data from dynamic tests of the thermal and mechanical equipment at power generating units with VVER-1000 and RBMK-1000 reactors includes the values of the lowest natural frequencies and the corresponding damping decrements for the chosen 1684 items of equipment. The data bank includes equipment for which the data from the dynamic tests can be treated uniquely (i.e., equipment with distinct resonance frequencies).

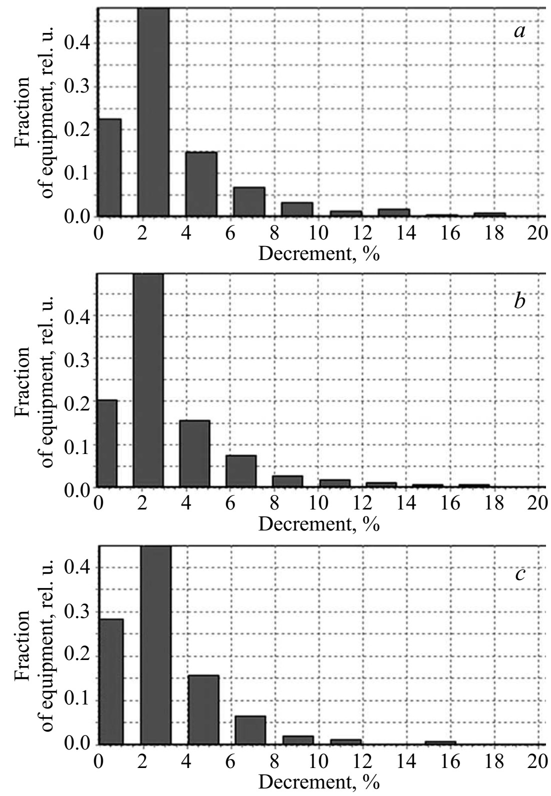

Fig. 2. Distribution of the damping decrements for frequencies $f < 33$ Hz for the X (a), Y (b), and Z (c) axes. The ordinate is the fraction of the pieces of equipment from all the groups for the X, Y, and Z axes, respectively.

TABLE 1. Classification of the Inspected Equipment

Group	Equipment
A	Equipment mounted on metallic frame components
B	Rectilinear sections of piping with concentrated mass: reverse valves, etc.
C	Ventilation units and other equipment mounted on spring vibration isolators
D	Ventilation equipment mounted on rubber (resin) vibration isolators or without vibration isolators
E	Vertically mounted vessels fastened to ceiling beams or suspension systems: filter-traps, heat exchangers
F	Horizontally positioned vessels with independent support structures mounted on the foundations or concrete bases: heat exchangers, tanks
G	Vertically positioned vessels with independent support structures mounted on concrete bases: heat exchangers with skirting supports
H	Equipment with housing wall thicknesses greater than 50 mm and attached to a concrete base: pumps, slab heat exchangers. Rigidly connected (“embedded”) equipment: heat exchangers and hermetic valves of ventilation systems, fire-fighting valves
I	Horizontally positioned vessels fastened to ceiling beams
J	Electrical equipment on shelves, attached to a base at several (4 or more) points
K	Piping fixtures with remote actuation (valves, slide valves, D_y 10 – 800) without independent supports (there are no supports under or near the fixture)
L	Piping fixtures with remote actuation D_y 10 – 800 with independent supports (immediately under or near the fixture)

The accumulated data base also contains the results of dynamic tests of mechanically autonomous (without external hookups) equipment at manufacturers as part of the certification of seismic resistance needed for further deliveries to nuclear power plants and at other industrial sites located at seismically hazardous regions of Russia and elsewhere. Certification was by computation and experiment with strict reproduction of actual conditions of disassembly and installation of equipment at the site where a piece of equipment is used. In the course of these certifications a total of about 150 samples of various equipment was studied for seismic resistance.

The results of a statistical analysis of the complete data bank of results from the dynamic tests are given below. The “small perturbation” factor is taken into account with the nominal assumption that the damping decrements for small interactions will be smaller than those for actual seismic interactions by no more than a factor of 1.5. Thus, here it is

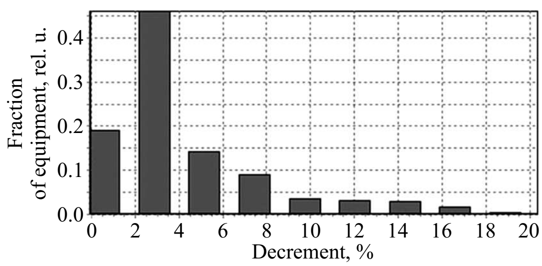

Fig. 3. Distribution of the values of the damping decrements for the *X* axis at frequencies $f < 10$ Hz: the ordinate is the fraction of pieces of equipment from all groups for the *X* axis at $f < 10$ Hz.

proposed that a correction for the "small perturbation" factor be introduced in the form of a multiplicative factor of 1.5 applied to all the damping decrement values given in the complete data bank. However, primary reliance should be on analyses without these corrections included, since a real estimate of the influence of the "small perturbation" factor on a determination of the damping decrements would require numerous experiments on different equipment under field conditions with assignment of dynamic interactions to its support structures with accelerations equivalent to actual seismic interactions. In addition, the actual influence of this factor is small and yields a small additional extra durability.

The damping decrements and natural frequencies along three different axes (directions of dynamic interactions) were analyzed. The directions of the axes for all the groups of equipment (Table 1) were chosen in the following way: the *Z* axis is always directed vertically upward, except in groups *K* and *L*, where the *Z* axis is directed along the shaft of the fixture. The *X* axis was along the axis of symmetry (or along the pipe for fixtures) and the Y axis was perpendicular to the *X* axis except when the axis of symmetry was the vertical axis *Z*.

Figure 1 is a plot of the distribution of the natural frequencies for all the types of equipment and all directions. Figures 2 and 3 are plots of the distributions of the damping decrements. The statistics for the entire data bank are listed in Table 2. The results of differentiated (by the groups of equipment in Table 1) statistics without and without corrections for the "mall perturbation" factor are listed in Table 3.

The distributions of the values of the damping decrements for all types of equipment and for all directions with and without corrections for the "small perturbation" factor are shown in Fig. 4.

The fraction of frequencies in the most critical range for seismic resonances, 0 – 10 Hz, was 24%, while the fraction of especially critical cases ($f < 10$ Hz combined with a damping decrement $d < 0.02$) was 5.5, 6.8, and 4.6% for the *X*, *Y*, and *Z* directions without corrections, respectively, and 2.2, 2.4, and 1.9% with the correction.

Almost 1/3 of the entire list of equipment in the data bank had damping decrements below 0.02 without the correction factor and resonance frequencies below 33 Hz. But even when the "small perturbation" correction is taken into

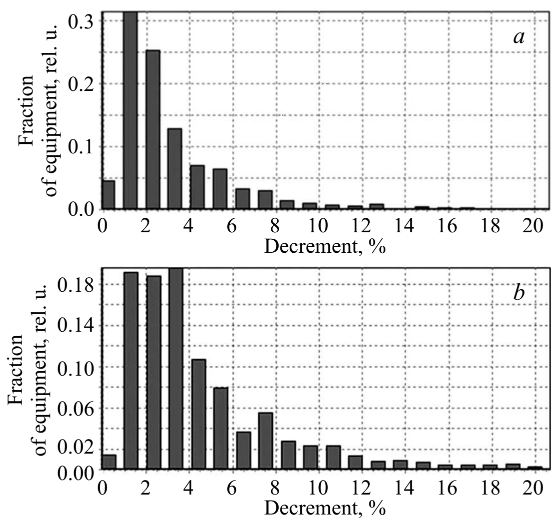

Fig. 4. Distribution of the values of the damping decrements for all axes at frequencies $f < 33$ Hz: *a*, without corrections; *b*, including the "small perturbation" factor; the ordinate is the fraction of pieces of equipment from the complete list of equipment.

account, about 15% of all the equipment do not meet the most conservative standards PNAÉ G-7-002–86 [7] which set a damping decrement of 0.02.

The differential statistics (Table 3) show that about 65% of all the equipment have a lowest frequency below 33 Hz and a damping decrement in the range 0.005 – 0.05; in each of the groups considered here the fraction of equipment with damping decrements below 0.02 ranges from 10 to 40%. This raises the legal issue of correcting the design specifications for the damping decrements for inertial loading of equipment by seismic and other external resonance interactions in the standards.

Since loading by seismic interactions is produced by a combination of dynamic characteristics (the frequencies, shape, and damping decrement of the oscillations), it is proposed that the minimum damping decrements listed in Table 4, which correspond to different directions of dynamic interactions and various frequency ranges, be adopted as

TABLE 2. Overall Statistics for the Values of the Damping Decrements in the Data Bank Based on Dynamic Tests of Thermal and Mechanical Equipment

Direction	Number of pieces of equipment, %			
	low frequencies ($f \leq 33$ Hz)		$f < 10$ Hz	
	$\delta < 0.02$	$0.02 \leq \delta \leq 0.05$	$\delta > 0.05$	$\delta < 0.02$
X	29.7/14.9	33.2/36.9	13.4/24.5	5.5/2.2
Y	35.0/16.4	33.2/40.2	13.3/24.9	6.8/2.4
Z	29.2/14.5	29.9/34.5	10.6/21.0	4.6/1.9

Note. The numerator is the percent of the entire list of equipment without corrections; the denominator is the percent of the entire list with a correction for the "small perturbation" factor.

TABLE 3. Differential Statistics of the Equipment

Group	Direction	Number of units of equipment, % of equipment in the group						Total in group, pieces
		low frequencies ($f \leq 33$ Hz)			high frequencies ($f > 33$ Hz)			
		δ <0.02	0.02 ≤ δ ≤ 0.05	δ > 0.05	δ <0.02	0.02 ≤ δ ≤ 0.05	δ > 0.05	
A	*X*	35.1/10.8	24.3/43.2	13.5/18.9	21.6/16.2	5.4/10.9	–/–	37
	Y	44.7/18.4	28.9/50.0	–/5.3	18.4/15.8	7.9/7.9	–/2.6	38
	Z	24.3/8.1	27.0/32.4	10.8/21.6	37.8/29.7	–/8.1	–/–	37
B	*X*	36.9/14.6	25.2/43.7	2.9/6.8	28.2/17.5	6.8/14.6	–/2.9	103
	Y	37.4/18.7	27.1/36.4	2.8/12.1	23.4/18.7	8.4/11.2	0.9/2.8	107
	Z	40.2/20.6	15.9/31.8	1.9/5.6	26.2/15.9	14.0/20.6	1.9/5.6	107
C	*X*	7.5/2.2	52.7/30.1	39.8/67.7	–/–	–/–	–/–	93
	Y	10.2/4.1	44.9/26.5	44.9/69.4	–/–	–/–	–/–	98
	Z	4.0/1.0	60.6/37.4	35.4/61.6	–/–	–/–	–/–	99
D	*X*	14.7/6.4	39.4/28.4	24.8/44.0	15.6/14.7	5.5/4.6	–/1.8	109
	Y	19.4/7.4	29.6/28.7	30.6/43.5	14.8/8.3	4.6/9.3	0.9/2.8	108
	Z	10.2/1.0	21.4/29.6	28.6/29.6	25.5/16.3	10.2/15.3	4.1/8.2	98
E	*X*	15.0/0.0	50.0/57.5	22.5/30.0	7.5/7.5	5.0/2.5	0.0/2.5	40
	Y	19.4/0.0	61.1/61.1	13.9/33.3	2.8/–	–/2.8	2.8/2.8	36
	Z	17.2/3.4	58.6/48.3	20.7/44.8	–/–	3.4/–	–/3.4	29
F	*X*	34.6/7.7	44.2/65.4	15.4/21.2	3.8/–	1.9/5.8	–/–	52
	Y	22.0/12.0	44.0/42.0	12.0/24.0	16.0/14.0	6.0/6.0	–/2.0	50
	Z	20.8/6.3	22.9/37.5	10.4/10.4	37.5/33.3	8.3/10.4	4.2/6.3	48
G	*X*	26.5.10.3	38.2/35.3	14.0/33.1	14.0/11.0	6.6/6.6	0.7/3.7	136
	Y	25.7/10.3	43.4/40.4	13.2/31.6	13.2/10.3	2.9/4.4	1.5/2.9	136
	Z	11.7/8.1	31.5/24.3	13.5/24.3	26.1/23.4	13.5/10.8	3.6/9.0	111
H	*X*	12.0/3.8	11.4/15.8	8.2/12.0	44.9/31.6	19.6/28.5	3.8/8.2	158
	Y	15.7/5.4	13.9/19.3	9.0/13.9	41.0/20.5	18.1/34.3	2.4/6.6	166
	Z	10.9/4.4	13.1/12.4	5.8/13.1	43.8/30.7	19.0/24.8	7.3/14.6	137
I	*X*	18.8/12.5	62.5/37.5	12.5/43.8	6.3/6.3	–/–	–/–	16
	Y	47.4/31.6	36.8/36.8	10.5/26.3	5.3/5.3	–/–	–/–	19
	Z	16.7/5.6	61.1/50.0	11.1/33.3	11.1/11.1	–/–	–/–	18
J	*X*	12.7/2.9	43.4/34.1	36.4/55.5	2.9/1.7	4.0/4.0	0.6/1.7	173
	Y	15.7/2.5	40.9/38.4	39.6/55.3	2.5/1.3	1.3/1.9	–/0.6	159
	Z	18.0/4.5	36.9/24.3	15.3/41.4	18.0/10.8	10.8/15.3	0.9/3.6	111
K	*X*	43.5/27.4	29.7/38.8	3.2/10.3	20.9/16.4	2.4/6.7	0.2/0.4	464
	Y	52.3/27.1	30.1/46.9	3.0/11.4	12.0/9.0	2.4/4.7	0.2/0.9	465
	Z	47.1/26.3	27.9/43.0	5.9/11.6	15.1/11.2	3.5/6.6	0.4/1.3	456
L	*X*	40.0/21.4	31.5/42.0	8.1.16.3	13.9/10.2	6.4/8.5	–/1.7	295
	Y	48.3/24.2	34.8/48.3	7.0/17.5	7.6/7.3	2.0/2.0	0.3/0.7	302
	Z	35.9/17.6	32.1/38.3	5.5/17.6	20.3/15.2	6.2/10.7	–/0.7	290
Total	*X*	**29.7/14.9**	**33.2/36.9**	**13.4/24.5**	**17.5/13.0**	**5.7/8.7**	**0.5/2.0**	**1676**
	Y	**35.0/16.4**	**33.2/40.2**	**13.3/24.9**	**15.6/9.3**	**4.3/7.3**	**0.4/1.8**	**1684**
	Z	**29.2/14.5**	**29.9/34.5**	**10.6/21.0**	**21.0/15.4**	**7.6/11.0**	**1.2/3.9**	**1541**

Note. The numerator is the percent of units of equipment in each group without corrections; the denominator is the percent of units of equipment in each group with a correction.

conservative standard values when actual experimental data are not available.

CONCLUSIONS

1. We have proposed a classification of equipment that is important for safe operation of nuclear power plants in terms of its dynamic behavior under seismic loading.

2. Based on an analysis of an extensive data bank of results from dynamic tests of the entire range of thermal and mechanical equipment in power generating units with VVER-1000 and RBMK-1000 reactors, we have studied the statistical behavior of the distribution of frequencies and damping decrements taking into account the “small perturbation” factor, which affects the measured damping decrement.

3. It has been found that about 65% of all the equipment has a lowest natural frequency below 33 Hz and a damping decrement in the range of 0.005 – 0.05% and that for each of the groups that were examined, 10 – 40% of the units have decrements below the value of 0.02% set in the standard PNAÉ G-7-002–86. Thus, there is a need to correct the stan-

TABLE 4. Minimum Values of Damping Decrements

Group	Direction	Lower limit of damping decrement without corrections			Lower limit of damping decrement with a coefficient of 1.5			Lowest frequency, Hz
		$f \leq 10$	$10 < f \leq 20$	$20 < f \leq 30$	$f \leq 10$	$10 < f \leq 20$	$20 < f \leq 30$	
A	*X*	0.062	0.010	0.012	0.093	0.015	0.018	6.3
	Y	0.030	0.009	0.008	0.045	0.014	0.012	8.8
	Z	0.039	0.012	0.007	0.059	0.018	0.011	6.0
B	*X*	0.012	0.008	0.007	0.018	0.012	0.011	5.3
	Y	0.011	0.007	0.005	0.017	0.011	0.008	4.0
	Z	0.010	0.008	0.005	0.015	0.012	0.008	4.0
C	*X*	0.012	0.011	No data	0.018	0.017	No data	1.5
	Y	0.012	0.017	0.011	0.018	0.026	0.017	0.9
	Z	0.013	0.013	0.009	0.020	0.020	0.014	2.7
D	*X*	0.014	0.008	0.011	0.021	0.012	0.017	2.3
	Y	0.025	0.009	0.009	0.038	0.014	0.014	2.0
	Z	0.016	0.016	0.019	0.024	0.024	0.029	3.0
E	*X*	0.014	0.017	0.013	0.021	0.026	0.020	4.5
	Y	0.014	0.013	0.016	0.021	0.020	0.024	4.0
	Z	0.018	0.012	0.021	0.027	0.018	0.032	3.0
F	*X*	0.014	0.012	0.010	0.021	0.018	0.015	4.2
	Y	0.020	0.010	0.009	0.030	0.015	0.014	3.3
	Z	0.029	0.016	0.011	0.044	0.024	0.017	4.8
G	*X*	0.012	0.007	0.014	0.018	0.011	0.021	4.8
	Y	0.011	0.005	0.011	0.017	0.008	0.017	4.8
	Z	0.024	0.010	0.007	0.036	0.015	0.011	5.4
H	*X*	No data	0.019	0.008	No data	0.029	0.012	10.5
	Y	0.080	0.010	0.010	0.120	0.015	0.015	2.9
	Z	0.050	0.013	0.007	0.075	0.020	0.011	8.7
I	*X*	0.015	0.011	No data	0.023	0.017	No data	6.5
	Y	0.027	0.012	0.012	0.041	0.018	0.018	3.8
	Z	0.029	0.018	0.014	0.044	0.027	0.021	8.7
J	*X*	0.010	0.012	0.010	0.015	0.018	0.015	3.0
	Y	0.014	0.008	0.019	0.021	0.012	0.029	2.7
	Z	0.016	0.014	0.010	0.024	0.021	0.015	4.0

dard specifications for the choice of design values for damping decrements under inertial loading of equipment from seismic interactions.

4. Minimum values of the damping decrements for all the types of equipment examined here as functions of the direction and natural frequencies of dynamic interactions have been proposed for adoption as conservative standard values for use in design estimates of seismic stability when no real experimental data are available.

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