Fitting of a Piping-Support Finite Element Model by Means of Measured Modal Parameters

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Abstract

Dynamic investigations were carried out on a fixed piping support. fastened to a concrete block by safety dowels. and tie rods respectively. The primary objective was, to improve the parameters of a finite element model, especially the dynamic coefficients concerning the area between the concrete block and the steel plate. The fitting of the finite element model can be performed by indirect parameter identification. With this adjustment algorithm subsystems of the total system matrices are systematically fitted by means of modal parameters. In this application eigenvalues are used with the criterion to minimize the differences between measured values and calculated values from the finite element model.

Different test configurations were studied, e. g., small and large contact surfaces between steel and concrete. different tightening torques and a weak as well as a stiff steel plate construction.

For the different test series the stiffness coefficients of the concrete and steel plate range were found with a very good correlation between the measured and calculated natural frequencies.

1. Introduction

Strong safety specifications require different dynamic calculations in the design stage of nuclear power plants. For safety related piping systems the effects of dynamic loads (earthquake. explosion etc.) have to be investigated and it has to be proved. whether the piping system resists specified loads.

In the finite element models usually the stiffness of the piping support steel construction is taken into account. but the anchoring of the suppports normally is considered to be completely fixed. However, the latest publications show. that the connections between the concrete and the steel plate of the support is very important for the load transfer from the building to the piping system and should be considered in the dynamic model.

In order to get a better knowledge about the dynamic characteristics - including the concrete-steel-plate area - measurements as well as finite element calculations were performed to obtain natural frequencies and natural modes. The measured as well as the calculated natural frequencies were used to determine the stiffness coefficients for the range of the concrete structure and the steel plate. The applied procedure starts with estimated stiffness values for the finite element model and improves this parameters by minimizing the differences between calculated and measured eigenvalues.

This paper describes the investigation method and presents results: natural frequencies and stiffness parameters for different system arrangements of the anchoring.

2. Experimental Arrangement

The test set-up is shown in figure 1. In the laboratory tests a fixed point support for a pipe of nominal size of 4 inch was employed. consisting of an anchor plate, a post and a clamp. The pipe was simulated by a rigid bar and the support was anchored to a concrete block by means of safety dowels (conical split sleeves), and tie rods respectively. For the section of interest of the investigation different test conditions (see also table I) could be realized:

a) full contact surface between the steel plate and the concrete block

b) reduced contact surface between the steel plate and the concrete block by means of supporting disks

c) variation of the tightening torque

d) variation of the stiffness of the anchor steel plate

3. Determination of Natural Frequencies and Modes by Means of Modal Analysis

Natural frequencies and natural modes were determined by means of experimental "Modal Analysis". In this procedure at first frequency response functions have to be measured for selected measurement points. Each response function can be found by exciting the system at a defined location and measuring the response at another location. In the second step the unknown modal parameters (natural frequencies and modes) can be calculated by adjusting analytical frequency response curves to the measured ones.

In the interesting frequency range from 5 to 100 Hz up to 6 natural frequencies were determined (see figure 2 and table II). The natural modes are characterized by torsional and bending deformations of the post, bending of the steel plate and in addition vertical and rotary movements of the whole test set up (figure 2).

4. Finite Element Calculation

Natural frequencies and modes can also be determined by calculation with a finite element model. The employed model consists of 20 beam elements (piping support and concrete block) and has 24 nodal points. The stiffness characteristics for the interesting area of the concrete block and the steel plate was modeled by a spring element with six stiffness coefficients, concerning the three translatory, respectively the three rotatory motions. The modal parameters depend on this stiffness coefficients and during the above mentioned fitting procedure the coefficients have to be changed, in order to get a good correlation between calculated and measured natural frequencies.

Calculation of the modal parameters was performed with a finite element computer program, using the Lanczos eigenvalue procedure.

5. Fitting of the Finite Element Model (Indirect Parameter Identification)

The first comparison between calculated and measured eigenfrequencies didn't show satisfactory results and a fitting of the finite element model seemed to be suitable. It was supposed, that most of the system matrix elements are correct and only a few of them e.g., the stiffness coefficients in the concrete-steel plate area have to be corrected. To improve these parameters a systematic adjustment algorithm has been selected /1/ and programmed. The procedure allows the fitting of the model by means of measured and calculated eigenvalues.

No problems occured, modelling the mass matrix $\underline{M}$. Therefore the adjustment could be limited to the stiffness matrix $\underline{K}$. Damping was not taken into consideration because of low damping in the investigated system. The free vibrations are described by the equations of motion,

$$\underline{M}\,\ddot{\underline{x}} + \underline{K}\,\underline{x} = 0 \qquad (1)$$

and the corresponding eigenvalue problem,

$$(\underline{K} - \lambda_l\,\underline{M})\,\varphi_l = 0 \qquad (2)$$

leads to the eigenvalues $\lambda_l = \omega_l^2$ (ω_l circular natural frequency) and the eigenvectors φ_l. The eigenvectors are considered to be normalized,

$$\varphi_l^T\,\underline{M}\,\varphi_l = 1 \qquad (3)$$

As mentioned before partitioning of $\underline{K}$ is possible into a matrix $\underline{K}_o$ with parameters, not to be changed and submatrices $a_n\underline{K}_n$, which shall be corrected,

$$\underline{K} = \underline{K}_o + \sum_{n=1}^{N} a_n\,\underline{K}_n \qquad (4)$$

a_n are the correction factors. Premultiplication of (2) with φ_l^T and substitution of (3) and (4) leads to

$$-\lambda_l + \varphi_l^T\,\underline{K}_o\,\varphi_l + \varphi_l^T\,\Big(\sum_{n=1}^{N} a_n\,\underline{K}_n\Big)\,\varphi_l = 0 \qquad (5)$$

Eq. (5) expresses the eigenvalues λ_l of the finite element model in terms of the correction factors a_n. The objective is, to determine these factors in that way to minimize the residuals v_l,

$$v_l = \lambda_l^M - \lambda_l = \lambda_l^M - \varphi_l^T\,\underline{K}_o\,\varphi_l - \varphi_l^T\,\Big(\sum_{n=1}^{N} a_n\,\underline{K}_n\Big)\,\varphi_l \qquad (6)$$

which are the differences between the measured eigenvalues λ_l^M and the corresponding λ_l of the model. The partial derivative

$$\frac{\partial v_l}{\partial a_n} = -\,\varphi_l^T \cdot \underline{K}_n\,\varphi_l \qquad (7)$$

points out the sensitivity of the eigenvalue λ_l with respect to submatrix $\underline{K}_n$.
If we consider several eigenvalues the residuals can be arranged in matrix notation

$$\underline{v} = \underline{b} - \underline{D}_v \cdot \underline{a} \qquad (8)$$

with the vector elements

$$b_l = \lambda_l^M - \varphi_l^T\,\underline{K}_o\,\varphi_l \qquad (9)$$

and the matrix elements

$$D_{v_{ln}} = \varphi_l^T\,\underline{K}_n\,\varphi_l \qquad (10)$$

Minimizing the residual vector $\underline{v}$, respectively the objective function, included a weight matrix $\underline{W}$,

$$J_{(a)} = \underline{v}^T \underline{W} \underline{v} \tag{11}$$

leads to a linear equation system, which can be solved for the unknown parameters $\underline{a}$

$$\underline{D}_v^T \underline{W} \underline{D}_v \cdot \underline{a} = \underline{D}_v^T \underline{W} \cdot \underline{b} \quad \text{(iterativ)} \tag{12}$$

If $\underline{v}$ is a nonlinear function of $\underline{a}$, the unknown parameters have to be determined by linearization. The algorithm has been programmed and tested, the piping support model was adjusted by means of the described method. After the submatrix correction new eigenvalues are analyzed. If the correlation between measured and calculated eigenvalues is still unsatisfied, a further calculation of $\underline{a}$ is necessary.

6. Analysis Results

Starting from the original piping-support finite element model the fitting procedure yields the following results (tables II and III). The translatory stiffness k_{11}, k_{22} in the horizontal directions as well as the rotary stiffness k_{66} about the vertical axis are very high. However, the vertical stiffness k_{33} and the rotary stiffness k_{44}, k_{55} about the horizontal axes cannot be ignored. k_{33} is nearly constant for the different configurations and depends particulary on the anchor plate stiffness. Especially the 6th mode is influenced by this stiffness. The corresponding natural frequency couldn't be measured in the cases Z46VA, D25USM and D00USM. Therefore the k_{33}-values are not available in table III.

k_{44} and k_{55} are equal to each other, which can be explained by equal geometric relations in the two directions. The 4th and 5th modes depend very strongly on this stiffness coefficients (table III and figure 2). The variation of the tightening torque has great influence on k_{44} and k_{55}, on the other hand the size of the contact surface has only little effect, probably influenced by the low concrete pressure. Stiffening of the anchor plate leads to a large stiffness increase of k_{44} and k_{55}, consequently a shift of the natural frequencies (table II) especially in the higher frequency range.

Besides the requested stiffness effects in the anchor plate - concrete block range other effects have been found by means of the fitting procedure. The vibrations due to torsion (1st mode for unstiffened anchor plate and 2nd mode for stiffened anchor plate) could be correctly determined by consideration of the warping effect, which is important for open cross section elements. The torsion constant of cross section had to be corrected by a factor of approximately ten to obtain a good correlation between calculated and measured natural frequencies.

7. References

/1/ Natke, H. G.
Einführung in Theorie und Praxis der Zeitreihen- und Modalanalyse. Identifikation schwingungsfähiger elastomechanischer Systeme
Vieweg-Verlag, 1983

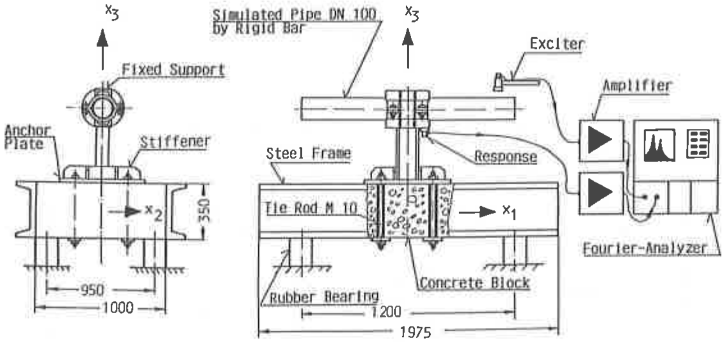

Figure 1: Test set-up with tie rod connection

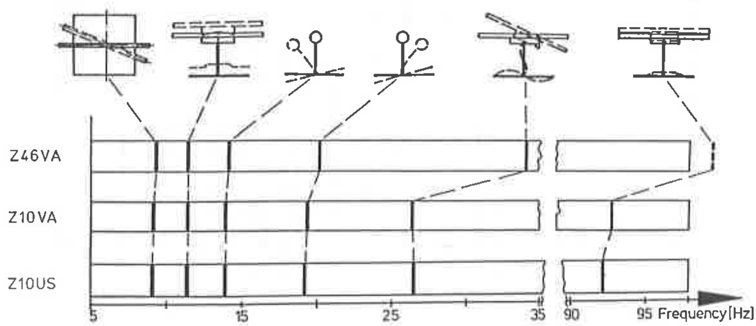

Figure 2: Natural frequencies and modes of piping system with tie rods M10

Table I: System variation of test set-up "Piping Support DN 100" (normal size 4 inch)

Test Series Designation	Anchoring	Tightening Torque	Contact Surface between Anchor-Plate and Concrete Block	Anchor-Plate Stiffening
Z 46 VA	tie rod *)	46 Nm	full contact	no
Z 10 VA	tie rod	10 Nm	full contact	no
Z 10 US	tie rod	10 Nm	4 supporting-discs	no
D 25 VAO	dowel **)	25 Nm	full contact	no
D 25 USO	dowel	25 Nm	4 supporting-discs	no
D 00 USO	dowel	0 Nm	4 supporting-discs	no
D 25 USM	dowel	25 Nm	4 supporting-discs	yes
D 00 USM	dowel	0 Nm	4 supporting-discs	yes

*) tie rod 4 x M10 **) dowel 4 x M8 (conical split sleeves)

Table II: Comparison of measured and calculated (adjusted) natural eigenfrequencies

Test Series **)		Eigenfrequencies Hz					
		f_1 *)	f_2 *)	f_3	f_4	f_5	f_6
Z46VA	measured	9,22	10,52	14,12	20,13	34,06	-
	calculated	9,22	10,47	14,16	20,12	34,06	-
Z10VA	measured	9,22	10,52	14,12	19,49	26,47	92,89
	calculated	9,22	10,46	14,05	19,40	26,47	92,89
Z10US	measured	9,22	10,52	14,12	19,32	26,61	92,35
	calculated	9,22	10,46	14,05	19,42	26,60	92,35
D25 VAO	measured	9,22	10,52	14,12	19,72	29,07	95,46
	calculated	9,22	10,46	14,10	19,69	29,07	95,46
D25 USO	measured	9,22	10,52	14,12	19,47	27,20	94,40
	calculated	9,22	10,46	14,06	19,49	27,20	94,40
D00 USO	measured	9,22	10,52	14,12	19,29	24,64	93,57
	calculated	9,22	10,46	14,00	19,16	24,65	93,57
D25 USM	measured	10,58	12,69	14,77	24,49	36,06	-
	calculated	10,47	12,69	14,85	24,09	36,11	-
D00 USM	measured	10,58	12,69	14,77	24,07	33,93	-
	calculated	10,47	12,69	14,84	23,83	33,99	-

*) After stiffening the anchor plate there is a change of modes

**) See table 1 for designation

Table III: Systematic adjusted boundary stiffnesses of concrete to steel connection

Test Series *)	Adjusted Boundary Stiffness k_{33} kN/m	$k_{44} = k_{55}$ kN.m/rad
Z46VA	—	2568,98
Z10VA	40604,2	778,01
Z10US	40093,4	791,43
D25 VAO	43107,9	1111,01
D25 USO	42065,5	856,90
D00 USO	41259,8	613,41
D25 USM	—	1948,33
D00 USM	—	1489,29

*) see table 1 for designation