

ON THE OPTIMIZATION OF SUPPORT POSITIONING AND STIFFNESS FOR PIPING SYSTEMS IN POWER PLANTS

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ABSTRACT

The optimal location of supports for the reduction of vibration in piping systems is an interesting structural problem, that can be approached also with the methods used in the updating parameters problems, especially when the cause of the vibration is due to a resonance or a ineffective damping level, and the shift of a critical frequency is an effective remedy. In the proposed paper a frequency domain method of Finite Element model updating is used in order to properly locate the natural frequencies of a given piping system, starting from the nominal condition. The method considers modal parameters, and enables to directly update the physical quantities of the finite element model, i.e., in the considered application, the stiffness and damping of the supporting devices. The model of the structure is made up by beam finite elements, lumped springs and masses, and rigid links. The general procedure is applied here updating the stiffness and location of the supports of the piping according to the comparison among the current frequencies of the piping systems structure and the ones that are required, according to specific requirements. Application to a system similar to a portion of an actual AP1000 (a new Advanced Passive Nuclear Reactor) piping-support layout is presented.

Keywords: Piping vibration, support optimization, FEM updating, sensitivity analysis.

1. INTRODUCTION

The reduction of vibration in piping systems when their occurrence is of concerns for the plant is an interesting structural problem (Sukai, 2002), that can be faced, among the other means, through the optimization of the localization and the stiffness of the supports of the piping system.

Elastic and rigid supports can be used for piping systems: the first enable more easily to proper tuning the frequencies of the piping structure, but they require more maintenance and have a more complex structure with respect to the stiff supports, which can tune the frequencies of the piping structure only by means of their location and direction.

The use of elastic support localization in order to create a periodic system and thus generate stop band frequency and passing band frequency suitably located with respect to the excitation spectrum, has been investigated by Koo (1998) for a simple piping system, made of two short straight lines and a double curve. In that application the use

of four elastic vertical supports, instead of a single rigid support is investigated, in the high frequency range, i.e. up to 500Hz. In the mentioned application the piping conveying the fluid is reproduced by means of the wave approach, i.e. considering the equations in the frequency domain of straight and curved pipe elements, and adopting the transfer matrix technique (Koo, 1996). The method has been applied by the same authors to the analysis of the vibration behavior a piping of a Korean power plant (Koo, 2000), where no supports are provided, in order to get the highest simplification in the piping layout.

In another application (Kratz, 2003) the elimination of a snubber and the use of rigid support, partially relocated with respect to the position of the original spring hanger, has been used to modify the dynamic response of a high pressure injection system of a PWR. The forcing terms are related to the closing of a check valve, that generates a pressure impulse inside the pipe and the equations are integrated in the time domain considering fluid-pipe interaction. The comparison between the elastic support configuration and the rigid support configuration is carried out looking at the dynamic stress values in some significant points.

In the present paper the optimal location of elastic supports, aiming at shifting eventual resonant frequencies, is approached with the methods used in the updating parameters problems (Friswell, 1995). The adopted updating technique is based on the modal analysis of the structure, and updates the physical parameters of the piping (in the considered case the stiffness of the supports), minimizing a functional containing the current natural frequencies of the piping system, and the desired ones. The same technique has been already applied for the updating of a FEM model of a chemical plant piping systems (Collina, 2003), i.e. with the purpose of parameter identification. In the presented application, a piping system similar to that of the Passive Residual Heat Removal (PRHR) of the AP1000 nuclear reactor, is analyzed. The procedure for the choice of the supports location and stiffness is applied in order to obtain a dead band of frequencies for the horizontal modes between 5 and 15Hz. This aim is related to the earthquake excitation, and therefore is related only to the low frequency range. Problems due to fluid structure interaction are not treated here. The paper is organized as follows:

- outline of the numerical updating procedure, to relocate the supports and define their stiffness;
- description of the main features of the piping system under investigation and its schematization;
- application of the procedure;
- final remarks.

2. THE NUMERICAL PROCEDURE

The problem under consideration can be stated in the following way: how to locate the supports and determine their stiffness in order to suppress and/or shift certain natural frequencies and the related modes, without shifting to an undesirable values the other frequencies. In the presented application the requirements come from the input acceleration spectra due to earthquake action. The basic idea is to use a model updating technique, usually adopted for updating the physical parameters of a finite element model so that experimentally found frequencies are reproduced by the model, in a different way, modifying the frequencies of a structure in a desired manner, with precise objective values or band of frequency values.

The classical equation of a pipe conveying a non viscous flow at a given pressure and speed ([2], [3]), the following partial differential equation holds as indefinite equilibrium condition in the transversal direction is:

$$EI \frac{\partial^4 w}{\partial x^4} - (m_p + m_f) \frac{\partial^2 w}{\partial t^2} - (pA_{int} + m_f V^2) \frac{\partial^2 w}{\partial x^2} - 2m_f V \frac{\partial^2 w}{\partial x \partial t} = 0 \quad (1)$$

where EI is the flexural stiffness of the pipe, m_p and m_f are respectively the mass per unit length of the pipe and the fluid, A_{int} is the internal pipe cross area, V is the fluid speed, and w is the transversal motion of the pipe.

If the fluid speed is sufficiently low, then only the effect of the pressure can be retained, neglecting the Coriolis and the centrifugal term in (1), and a standard finite element approach can be used, considering the term due to pressure as a compressive tension acting on the beam element representing the pipe. The matrices of the system remain symmetric, and the eigenmodes are still real. Using f.i. the simplified approach reported in [9], it can be shown that, for the considered case, this approximation is fully consistent.

Once the structure is reproduced by finite elements and lumped elements, the eigenvalue-eigenvector calculations can be performed, considering the modes as real. It is reminded that this would not be possible, if the cross derivative terms are to be retained in equation (1), in case of high speed fluid, giving rise to complex modes.

The procedure of the updating parameters starts from the calculation of the i -th eigenvalue $\lambda_i = \omega_i^2$ derivative with respect to the generic j -th parameter θ_j , evaluated as:

$$\frac{\partial \lambda_i}{\partial \theta_j} = \Phi_i^T \left[\frac{\partial K}{\partial \theta_j} - \lambda_i \frac{\partial M}{\partial \theta_j} \right] \Phi_i \quad \text{with the normalization} \quad 1 = \Phi_i^T M \Phi_i \quad (2)$$

being M and K the mass and stiffness matrices of the finite element model, Φ_i the eigenvector (mode shape) related to the i -th eigenvalue. A sensitivity matrix $[S]$ is then assembled, by means of the derivatives (2), depending on the actual values of the parameters, through the related eigenvectors. A penalty function $J(\delta\theta)$ is used as object function:

$$J(\delta\theta) = \varepsilon^T W_{\varepsilon\varepsilon} \varepsilon + \delta\theta^T W_{\theta\theta} \delta\theta \quad (3)$$

where $W_{\varepsilon\varepsilon}$ and $W_{\theta\theta}$ are weighting matrices, ε is the vector of the difference between the target frequencies and the current calculated ones, and $\delta\theta$ is the vector of the parameters variation. Following the minimization of the penalty function (3) with respect to the parameters in the sense of the least square, and making a discretization of the parameters variation in steps [1] (subscript k) the following matrix linear system is obtained:

$$\left[[S_k]^T [W_{\varepsilon\varepsilon}] [S_k] + [W_{\theta\theta}] \right] (\theta_{k+1} - \theta_k) = [S_k]^T [W_{\varepsilon\varepsilon}] (\lambda_o - \lambda_k) \quad (4)$$

where the sensitivity matrix are dependent on the parameters, through the eigenvectors of the k -th step, and the differences between the objective eigenvalues λ_o and the current ones λ_k at k -th step. An iteration procedure is then set up, updating the sensitivity matrix at each step, as depicted in the chart flow in Fig.1.

The $W_{\varepsilon\varepsilon}$ weighting matrix can be used to distinguish, among the target frequencies, which are of greater importance, while the $W_{\theta\theta}$ matrix can regulate the allowable variation of the parameters. It has already been shown in [7] that a higher rate of allowable parameter variation increases the speed of convergence, but can also give rise to oscillation in the values of the parameters reached during the iteration process, while too low values of allowable parameters variation may prevent the parameters to reach their value, especially when several interacting parameters are present.

The sub cases in which the number of updating parameters is greater than the number of target values of frequencies (under determined case), or viceversa (over determined) can be managed, thanks to the introduction of the second weighting matrix.

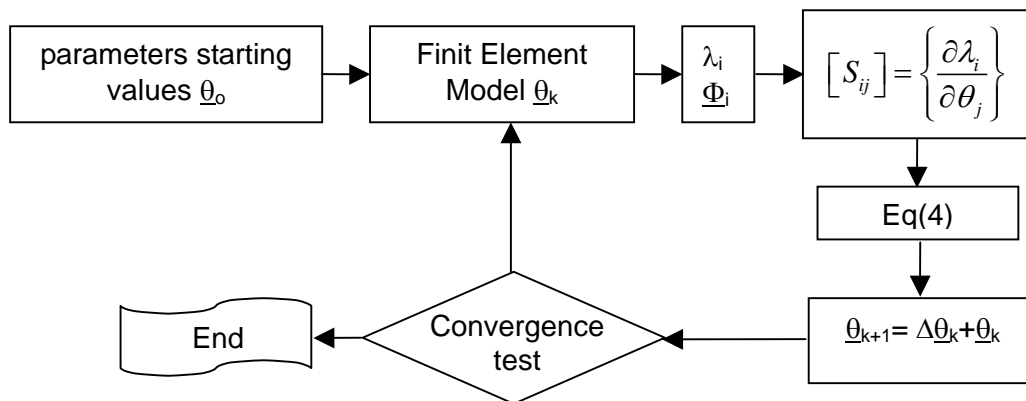


Figure 1 Flow-chart of the updating procedure.

3. APPLICATION OF THE PROCEDURE TO THE PIPING SYSTEM UNDER CONSIDERATION

The Passive Residual Heat Removal (PRHR) return piping that is analyzed, is composed of 14 inches pipes from the PRHR Heat Exchanger nozzle to the Steam Generator (SG) lower plenum nozzle. The piping system can be divided into three main parts, shown in Fig.1 in a unique isometric view. Starting from the steam generator a single pipe conveys, through a valve, to a central part with a double closed loop with two valves, with a final part conveying to the heat exchanger. The excitation input that is considered for the present analysis is the ground acceleration spectrum due to seismic action for the longitudinal (x) and lateral (y) direction. Combining the two spectra, the lowest value of the excitation lies in the 3÷5 Hz band and beyond 15Hz, therefore the aim is to displace

the frequencies of the horizontal modes inside the two previously mentioned intervals of frequency, while for the vertical modes a narrow minimum of the input spectrum in vertical direction exists in the range 8÷9 Hz. The targets are the following:

- avoid horizontal (x,y, and combined x-y) modes in the range 5÷15 Hz, and below 3Hz;
- place vertical modes in the narrow band 8÷9 Hz.

With these objectives, the structure under consideration was investigated. Several possibilities are open on how to pursue the frequency relocation, acting on the stiffness and location of the supports. A first attempt has been made starting from the actual location of the supports, considered as rigid, i.e. with a high value of stiffness, of the order of 10^9 N/m, and using the procedure to update these stiffness, and to test the sensitivity to the inclusion of other supports. This approach could not bring to satisfactory results, because the previously recalled initial stiffness was so high that the sensitive matrix was too low, and the matrix coefficient of the eq.4 was ill conditioned. An alternative approach had then to be used, also because the main interest lies in the possibility to explore several support location at the same time. Therefore the configuration shown in Fig.2 (right) has been considered as the starting one, in which most of the possible support locations have been considered, but with a values of the starting stiffness, set at $3 \cdot 10^6$ N/m, sufficiently low to equalize the sensitivity of the frequencies to the effect of all the supports, but stiff enough to give significant values of most of the sensitivities. (just one comment: actually the stiffness at the beginning is higher, and the assumption of rigid support around E9 is done: after the piping stress analysis that the design of support is obtained with the real stiffness) The frequencies of the starting reference system have been calculated, and the first obtained frequencies are listed in the Table 1, while the mode shapes of the first six frequencies are reported in Fig.3. The subsequent Fig.4 gives a graphical representation of the matrix of the sensitivities, expressed in a non dimensional form, giving a visual perception of the influence of the 21 parameters, i.e. the stiffness of the vertical and lateral supports. shown in Fig2. Where the values of sensitivities are low, a negligible influence can be inferred.

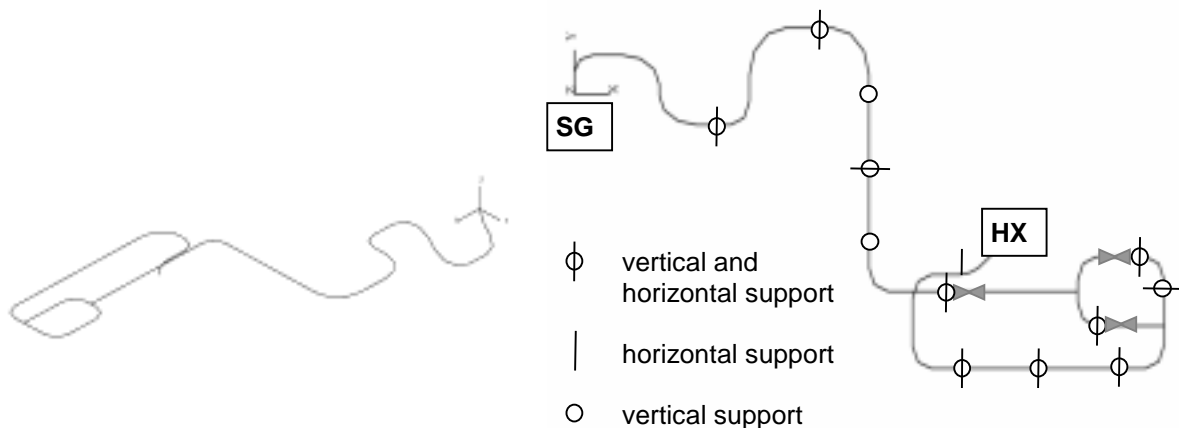


Figure 2 Complete ensemble of the PRHR line, shown as FEM. Left: isometric view. Right: top view with the indication of the valves and the location of the supports considered in the initial reference model. The final supports locations will be among the ones shown here.

Table 1 Calculated frequencies for the starting, the intermediate and the final configuration.

N.	Starting configuration [Hz]	Target values [Hz]	First intermediate configuration [Hz]	Final configuration [Hz]
1	5.68	4.0	3.96	4.02
2	6.25	4.5	4.54	5.03
3	6.66	5.0	5.25	5.24
4	7.78	8.0	8.00	8.4
5	8.08	8.5	8.43	8.2
6	8.98	9.0	9.00	8.7

7	10.10	15.0	15.22	15.6
8	11.15	16.0	16.00	15.7
9	12.90	17.0	16.95	17.1

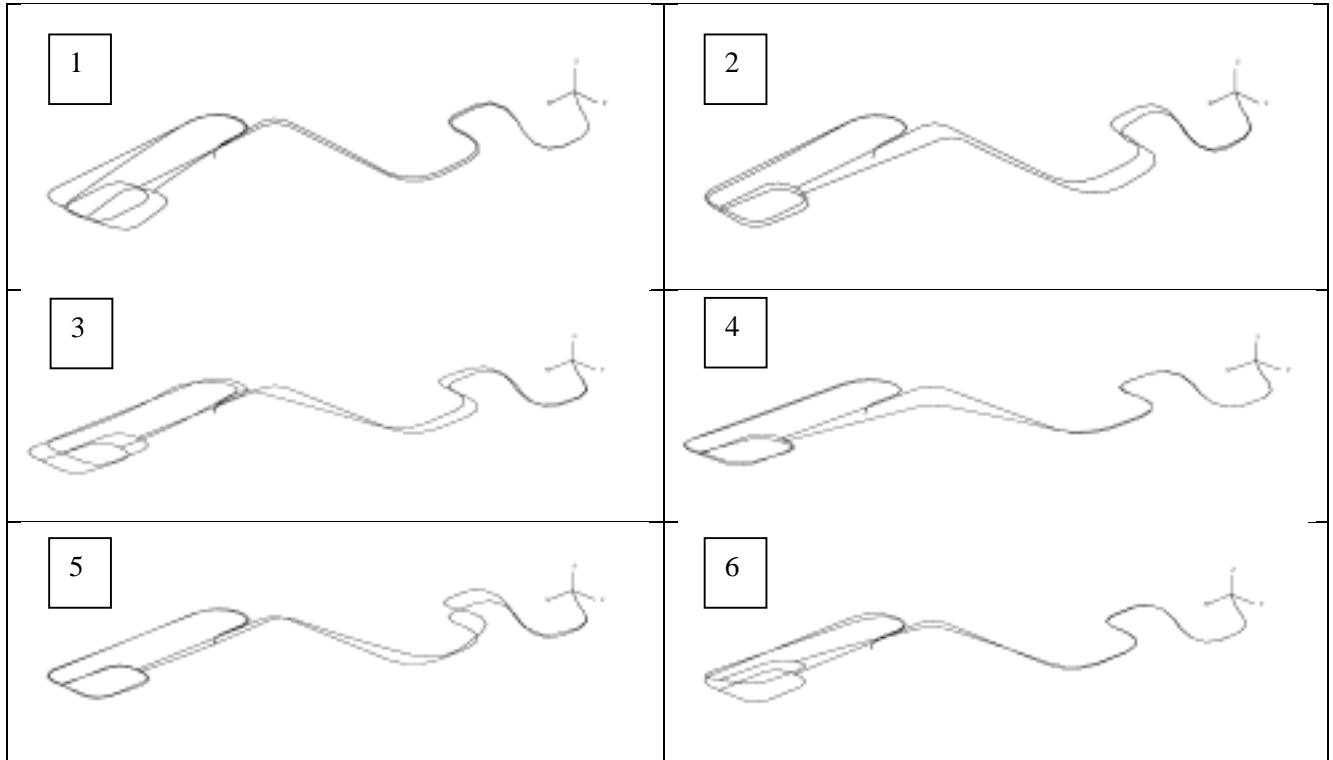


Figure 3 Mode shapes of the first six frequencies of the initial reference configurations. The numbers refer to the Table 1 list.

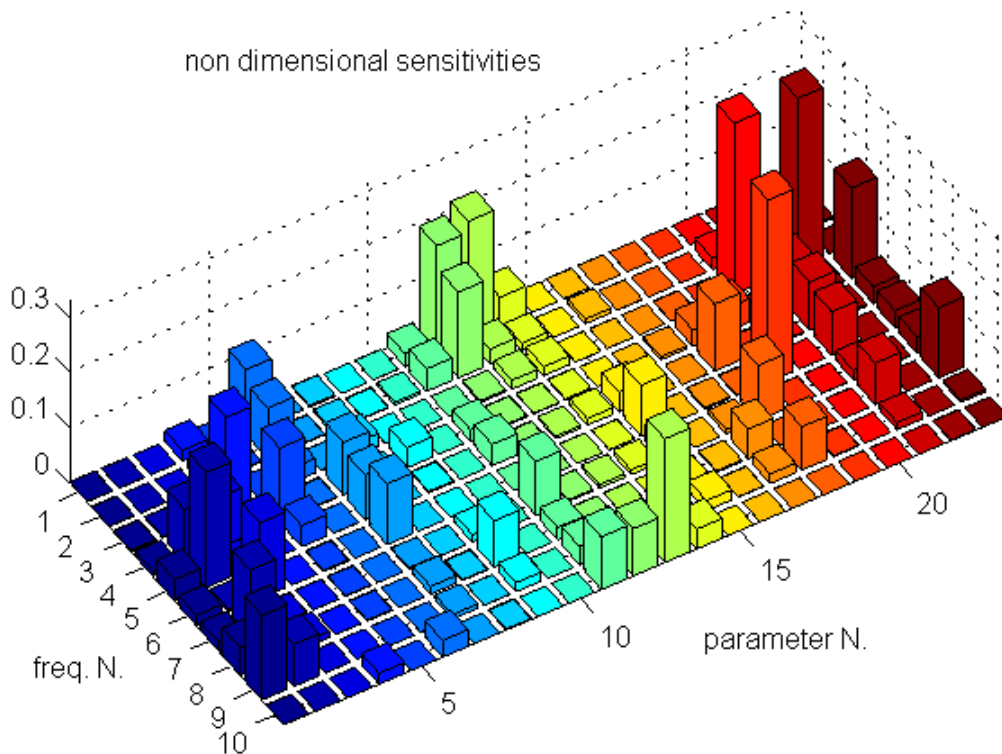


Figure 4 Graphical representation of the non dimensional sensitivity matrix for the reference configuration, as a function of the frequency number (refer to the list of Table 1), and to the considered stiffness parameters.

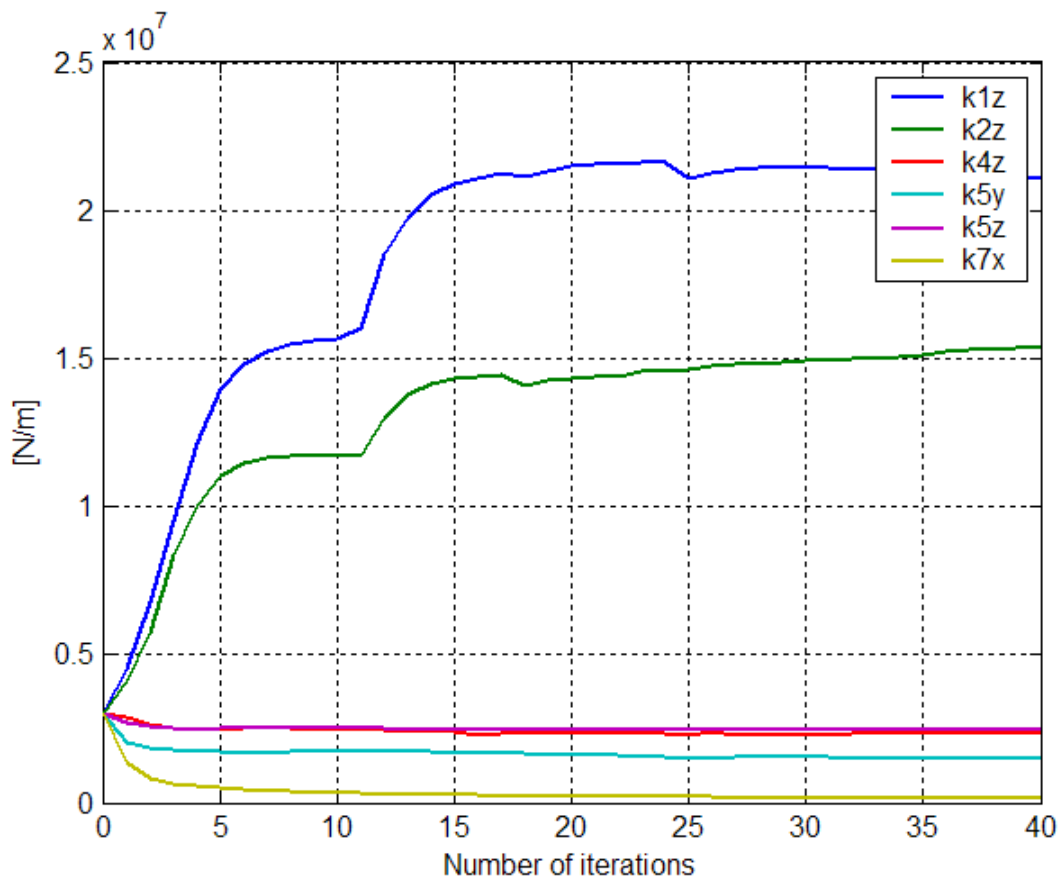


Figure 5 Trend of the first six parameters, vs. the number of iterative steps.

Looking at this representation (Fig.4), it is expected that the updating procedure should give more importance to the parameters that have greater influence, and automatically discard the ones that have a smaller influence. In this way, a first automatic selection between the supports can be performed, and at the end of the first application of the procedure a selection of the supports that are worth to be retained is available.

As an example, in Fig.5, the trend of the first six parameters vs. the iteration steps is shown. Several observation can be drawn:

- some parameters reach a very distant value from their original one. Especially for these parameters the reciprocal influence is put in evidence from the trend that shows an apparent first steady level, that changes because of the modification of other parameters that in turn modify the terms of the sensitivity matrix;
- some parameters remains almost constant;
- other parameters decrease their value, this means that their presence is not necessary for the purpose of reaching the target frequencies. These represent the stiffness that can be eliminated from the model.

The subsequent Fig.6 shows the trend of the frequencies of the modes in the horizontal plane, i.e. having main displacement components in the x and y direction, and a negligible participation along the vertical direction. Looking at the separation of the modes at the end of the iteration process, the target of the dead band in the range 5÷15 Hz is reached, while (see Table 1) the first three vertical modes remain close to 8÷9 Hz narrow interval. The obtained results can not be nevertheless immediately used in practice, because a high number of support are required, and all of different stiffness.

Therefore, after this first run, subsequent applications of the procedure are carried out, reducing at each run the number of the parameters, i.e. eliminating the single vertical, lateral and longitudinal support that exhibit the

lowest values of stiffness. The basic idea is that if the value of a parameter is low, it is expected that its presence may be not necessary for the purpose of obtaining the target frequency.

In this operation some operating requirements need to be taken into account:

- the location of the stiffness in the horizontal plane should not interfere with the thermal expansion of the pipe;
- at least one longitudinal or lateral support is needed
- vertical supports are preferably necessary in the location close to the valves, which represent a concentrated load due to their mass.

At the end a configuration which matches the required frequencies is obtained, but where all the supports have different stiffness. Since it is obvious that the stiffness of the support should not be scattered on many different values, as final step the parameters that exhibit similar values can be grouped in a single macro parameter, thus considering the sensitivity not with respect to the single parameter, but with respect to the group. This grouping is not easy to be performed at the beginning, where this would be a unfavorable constrain, but can be done at the end, where the procedure has naturally taken the system to the similar values of some of the stiffness.

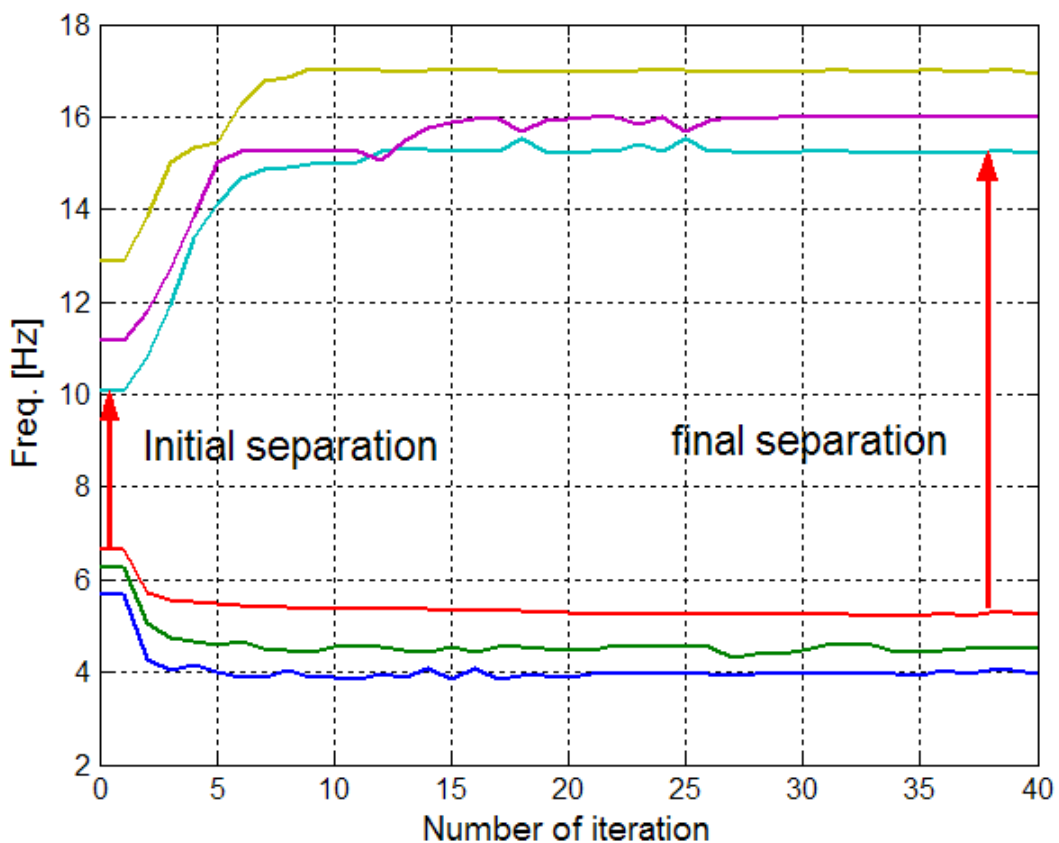


Figure 6 Trend of the frequencies of the horizontal modes (longitudinal, lateral, and combined longitudinal lateral) vs. the number of iterative steps. Run starting from the reference configuration.

Table 2 Final values of the remaining support stiffness, grouped in similar value. The indication of the color refer to Fig.7.

Group 1 (blue)	$0.19 \cdot 10^8$ N/m
Group 2 (red)	$0.54 \cdot 10^7$ N/m
Group 3 (green)	$0.19 \cdot 10^7$ N/m
Group 4 (black)	$0.13 \cdot 10^7$ N/m

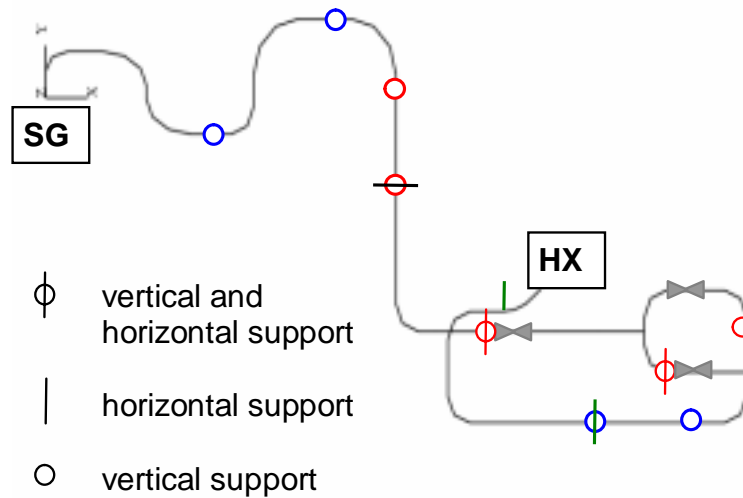


Figure 7 Location of the remaining support for obtaining the target frequencies. The colors refer to the different stiffness values, reported in Tab.II.

5. CONCLUDING REMARKS

A procedure to update and relocate the supports of a piping system has been presented, and applied as an example to a piping similar to the Passive Residual Heat Removal of the AP1000 Reactor. The procedure demonstrated to be effective in creating dead band intervals for given direction of vibration, so minimizing the input due to seismic excitation. The procedure needs to start from a reference configuration where all the possible location and direction of the support are to be included, but considering an optimal value of the stiffness, in order to have a significant value of the sensitivity, and to equalize the influence of all the stiffness.

Repeated applications of the procedure leads to the subsequent elimination of the stiffness of lower values, assuming that these are of less importance in the determination of the target frequency.

As final step, it is possible to reduce the number of different stiffness, creating groups of stiffness, that can be treated as a single macro parameter. At the end of the presented application, four different values of stiffness are required to reach the target frequencies.

As for the practical application, more investigation is needed in order to assess if all the constraints and/or requirements, from one side concerning static (deadweight and thermal expansion) and seismic (SSE) loads and from another side the compatibility with existing layout, support feasibility-functionality, metallic and civil structures, can be verified by the obtained set of support stiffness; in addition to this all the plant engineering constraints are giving some limits to the initial selection of the supports.

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