MASTER

COMPARISON OF LMFBR PIPING RESPONSE OBTAINED USING RESPONSE SPECTRUM AND TIME HISTORY METHODS

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ABSTRACT

The dynamic response to a seismic event is calculated for a piping system using a response spectrum analysis method and two time history analysis methods. The results from the analytical methods are compared to identify causes for the differences between the sets of analytical results. Comparative methods are also presented which help to gain confidence in the accuracy of the analytical methods in predicting piping system structural response during seismic events.

NOTATION

A_j^i	=	total piping support spectral acceleration in the jth direction given by the ith directional earthquake
$A_j^i(t)$	=	total piping support acceleration time history in the jth direction given by the ith directional earthquake
$A_n(t')$	=	piping support time history with modified time scale
$A_o(t)$	=	piping support time history with normal time scale
a_j	=	spectral acceleration in the jth direction from the jth directional response spectrum
$a_j(t)$	=	acceleration time history in the jth direction from the jth directional earthquake
θ_j	=	torsional spectral acceleration due to the jth earthquake from the jth torsional response spectrum
$\theta_j(t)$	=	torsional acceleration time history due to the jth earthquake
Φ_j	=	rotational spectral acceleration due to the jth earthquake from the jth rotational response spectrum
$\Phi_j(t)$	=	rotational acceleration time history due to the jth earthquake

F_j = axial force in the jth direction

J_a = J coordinate distance between the piping system support point and the reactor center of mass point

M_j = Rotational moment about the jth axis

R = total piping response

R_j^i = piping response from the jth direction spectral acceleration produced by the ith direction earthquake

R_{jk}^i = piping response from the kth mode shape produced by the jth direction spectral acceleration given by the ith direction earthquake

$R^i(t)$ = piping response time history produced by the ith direction earthquake excitation time history

INTRODUCTION

Heat transport system piping in nuclear power plants must be designed to withstand earthquake shocks. Often in the design verification procedure a dynamic analysis is performed using a finite element idealization of the piping system subjected to the seismic event. Two methods of dynamic analysis commonly accepted for use in seismic design are the response spectrum method and the time history method. Using the response spectrum method, piping system responses are approximately calculated and the analysis is relatively inexpensive to perform. Time history analysis procedures, which directly integrate the discretized piping system equations of motion, calculate piping system response during a transient event with greater mathematical accuracy but are more expensive to perform than a response spectrum analysis. Before performing time history analyses of a piping system undergoing seismic excitation, it would be helpful to obtain an estimate of the degree of difference in predicted structural response which could be expected when using time history analysis methods rather than response spectrum analysis methods.

The purpose of this paper is to present the methods used to compare piping system structural responses calculated using a response spectrum analysis and time history analysis methods in order to obtain an estimate of differences inherent between the two analytical techniques. In addition, comparison methods are discussed which are used to check the analytical techniques for possible computational errors.

For this study, the dynamic response analyses were conducted using a finite element idealization of a prototypic liquid metal fast breeder reactor piping leg, shown in Figure 1.

Seismic Excitation

Seismic events for nuclear power plant piping systems are characterized by three directional earthquake shocks, one in the vertical direction and one in each of the two horizontal directions (E-W, N-S). The earthquake shocks are altered before reaching the heat transport piping systems by the dynamic responses of the reactor containment buildings and major components. To obtain seismic excitations that could be used in seismic analyses of the piping systems, a complete analysis of the power plant buildings and support foundation was performed. This analysis is summarized in (1).

The results from the complete building analysis consist of seven response time histories at the center of mass of each building floor. Each horizontal earthquake produced a translational building response parallel to the earthquake shock direction, a rotational building response, and a torsional building response. The vertical earthquake shock produced a vertical translational building response. Before performing seismic analyses of the piping systems, the seven building floor response time histories are modified using the procedures described below.

Response Spectrum Analysis

Development of the seismic response spectra used for the response spectrum modal analyses and the procedure used to combine the analytical results are described to aid in discussing the comparisons between response spectrum modal analysis results and time history analysis results. Response spectra are computed from the seven building response time histories. To account for possible structural frequency variation owing to uncertainties in material properties of the structure and soil, the response spectra of the building floor are smoothed and the response spectra peaks are broadened (2). Additionally, for this study, the "valleys" in the response spectra were removed. To obtain design response spectra applicable at support points of a piping system, the design response spectra at the center of mass of the building floor are translated and combined, using the following equations (1) and the coordinate system shown in Figure 2.

$$A_x^x = a_x + Y_a \theta_x \tag{1}$$

$$A_x^y = Y_a \theta_y \tag{2}$$

$$A_y^y = a_y + X_a \theta_y \tag{3}$$

$$A_y^x = X_a \theta_x \tag{4}$$

$$A_z^z = a_z^z \tag{5}$$

$$A_z^x = X_a \phi_x \tag{6}$$

$$A_z^y = Y_a \phi_y \tag{7}$$

The design response spectra used in the seismic analyses of the piping system should envelope the design response spectra of all the piping support locations on the piping leg. That is, the design response spectra should be calculated at all piping support locations having large coordinate values X_a, Y_a and the design response spectra that have the largest acceleration amplitudes are used for the response spectrum analyses.

Seven separate response spectrum analyses were conducted and the results of these analyses are then combined to obtain the total structural response of the piping system. First, modal contributions to the structural response are combined for each response spectrum analysis. One accepted method of combining modal contributions, described in (3), is expressed as,

$$R^i_j = \left(\sum_{K=1}^{N} (R^i_{jk})^2 + 2 \Sigma \mid R^i_{jL} R^i_{jM} \mid \right)^{1/2} \qquad (8)$$

where the second summation is done on all L and M modes whose frequencies are within ten percent of each other. After the modal contributions are combined, the directional effects of the earthquake are combined to obtain the total structural response. From (1), one method used to perform this combination is expressed as,

$$R = [(R^x_x + R^x_y + R^x_z)^2 + (R^y_x + R^y_y + R^y_z)^2 + (R^z_z)^2]^{1/2} \qquad (9)$$

Time History Analysis

To obtain the transient dynamic piping system response during seismic excitation using time history analysis methods, separate analyses are performed, one for each of the three directional earthquake shocks. The seismic excitation time histories applied to the piping system are calculated from the building floor response time histories using the following equation set which was developed from the coordinate system shown in Figure 2.

$$A^x_x(t) = a^x_x(t) - Y_a \theta_x(t) \qquad (10)$$

$$A^x_y(t) = X_a \theta_x(t) \qquad (11)$$

$$A_z^x (t) = -X_a \phi_x (t) \quad (12)$$

$$A_y^y (t) = a_y^y (t) + X_a \theta_y (t) \quad (13)$$

$$A_x^y (t) = -Y_a \theta_y (t) \quad (14)$$

$$A_z^y (t) = Y_a \phi_y (t) \quad (15)$$

$$A_z^z (t) = a_z^z (t) \quad (16)$$

One horizontal earthquake is represented by the seismic excitation time histories calculated using Equations 10, 11 and 12. The second horizontal earthquake representation is calculated using Equations 13, 14 and 15 and the vertical earthquake excitation is calculated using Equation 16. The minus sign in Equation 10 and the plus sign in Equation 13 were calculated to be the most conservative way of combining the torsional and translational building response time histories.

One commonly accepted method of obtaining the total piping system response from the three time history analyses of the directional earthquake shocks involves algebraically combining the results from the three separate analyses at each time step (3). Although not explicitly stated, more than one combination of the three sets of results is necessary because the directional signs of the earthquake shocks are not known relative to each other. This can be expressed as,

$$R(t) = R^z(t) \pm R^x(t) \pm R^y(t) \quad (17)$$

There are four unique algebraic sign combinations of the three earthquake analysis results that should be evaluated in order to obtain the most conservative piping system response.

Additional time history analyses must be conducted to evaluate the possible frequency variations between the discretized piping system representation and the constructed piping system. This is accomplished by expanding and contracting the time scales of the seismic excitation time histories by ten percent. In equation form, this is expressed as,

$$A_n (t) = A_o (t \pm 0.1 t) \quad (18)$$

As with the standard time interval, three time history analyses, one for each directional earthquake shock, are performed using the expanded and contracted seismic excitation time histories. The results from these additional analyses must also be combined, using the method described above, to obtain the total piping system response during a seismic event. Therefore, there are twelve sets of combined time history analysis results which must be evaluated.

For this study, two time history analysis methods were used to calculate the piping system dynamic response produced by seismic excitation, and the structural response calculated using each method is compared to the response spectrum analysis results in the following section. One time history analyis method used is a form of the Newmark-beta direct integration scheme (4). Due to the extensive time and cost involved in performing direct integration time history analyses, only one direct integration time history analysis was performed for this study to obtain the piping system dynamic response when subjected to one of the twelve possible combinations of seismic excitation time histories.

The complete transient analysis of the piping system subjected to seismic excitation was conducted using the modal superposition time history analysis method. It was found that the modal superposition time history analysis method was particularly advantageous because the idealized piping system representation was linear, and only a small number of piping system parameter transient responses were desired, reducing the number of equations to be solved. Detailed discussions of the modal superposition time history analysis method can be found in a standard vibration text (5).

Only a small subset of modes significantly contributes to the dynamic response of the piping system during seismic excitation. Typically, piping modes having natural frequencies above 50 Hz do not contribute to the structural response, because the frequency of the dominant seismic excitation ranges between 0.1 Hz and 40 Hz. Including only those modes that significantly contribute to the piping structural response reduces the computer computational time. For this study, all piping modes were included that have natural frequencies below 50 Hz.

DISCUSSION

All piping system dynamic response analyses were conducted using the general purpose structural analysis computer program, WECAN (Westinghouse Electric Computer ANalysis) (6).

When comparing the piping system response calculated using the response spectrum analysis method and the time history analysis methods, the most direct approach is to compare the maximum total structural responses. Table 1 lists the reactor vessel nozzle loads calculated using the response spectrum method and the modal superposition time history method. Results from the Newmark-beta direct integration time history analysis are not included because the complete seismic analysis was not performed using this method. Comparing the results listed in Table 1, the modal superposition time history analysis results are between 11 percent and 42 percent lower than the response spectrum modal analysis results. All loads on the piping system were examined and the smallest percentage difference between the two sets of analytical results was 11 percent, which occurred for the reactor vessel nozzle moment, M_z. Thus, for the combination of the piping system and seismic excitation analyzed, the response spectrum method calculated conservative results.

There are two causes for the differences between the response spectrum analysis results and the modal superposition time history analysis results. First, the different results are produced by the different methods of combining the modal contributions used in the two analytical methods. For this study, the response spectrum method modal contributions were combined using Equation 8, which assumes that the maximum responses of the piping modes are unlikely to occur at the same instant in time while taking into account interaction between closely spaced modes. In the modal superposition time history method, the time and phase relationships between the individual modes are retained, so the modal contributions are linearly superposed at each time increment. These two different modal combination methods can produce widely varying differences in structural response, depending on the frequency spacing of the piping modes, the relative importance of modes to the total structural response, and the piping system excitation. Effects of the different modal combination methods on differences between response spectrum analysis results and modal superposition time history analysis results can not be determined before performing the time history analyses.

The second cause of differences between the two sets of analytical results is the difference between the developed seismic excitations used in the two analytical methods. Before performing time history analyses, estimates can be obtained on the effects that the differences in the seismic excitation input have on the differences between the response spectrum analysis results and the modal superposition time history analysis results.

Conservatism is introduced when generating a design response spectrum by broadening and smoothing a response spectrum computed from a seismic excitation time history. Expanding and contracting a seismic excitation time history introduces the same conservatism as broadening a response spectrum. The design response spectra used in this study have additional conservatism which was added by removing the "valleys" from the response spectra. The computed response spectrum of the vertical earthquake shock is shown in Figure 3. Also shown is the corresponding design response spectrum after the computed response spectrum was smoothed and broadened, and had its valleys removed. There is a noticeable difference between the two response spectra between 10 Hz and 16 Hz. Piping modes with natural frequencies that lie in the frequency bandwidth of the valleys, such as the 10 Hz to 16 Hz valley, will be computed to have larger modal contribution factors when using the response spectrum method rather than the modal superposition time history method. This difference in modal contribution factors can be easily identified in the calculated piping system response if the piping modes that lie in the valleys dominate the piping structural response. Therefore, differences should be identified between amplitudes of a design response spectrum and the amplitudes of the response spectra computed from the expanded, contracted, and normal seismic excitation time histories of the corresponding earthquake shock. By comparing these amplitude differences at the natural frequencies of the dominant piping modes, before performing the time history analyses, an estimate can be obtained of differences in the piping structural response calculated by the two analytical methods.

As an example of the above comparative method and to examine the analytical results for possible errors, the modal contributions of the 12.31 Hz mode to the reactor vessel nozzle loads, calculated using both analytical methods, are listed in Table 2. These modal contributions are produced by the vertical earthquake shock. The response spectrum analysis modal contributions are 24.5 percent larger than the modal superposition time history analysis modal contributions. For the vertical earthquake shock, at 12.3 Hz, the design response spectrum is 24 percent larger than the computed response spectrum. The percentage difference between the two response spectra at 12.3 Hz is identical to the difference in the modal contributions of the 12.3 Hz mode which were calculated using the two analytical methods. If the percent differences are not identical, then an error exists in one or both of the dynamic analyses. It should also be noted that the percent difference is the same between the modal contributions for all of the nozzle loads calculated using the two analytical methods. If the percent difference varies for different piping system loads, then an error exists in one or both of the dynamic analyses.

A check for absence of errors in the modal superposition time history analysis is performed by first obtaining the time at which the maximum response of a piping mode occurs when excited by the transient earthquake shock. A response spectrum is calculated from the time history of the same transient earthquake shock and the time obtained at which the maximum acceleration response develops, at the natural frequency of the piping mode being studied. If the time of the maximum modal response coincides with the time of the maximum acceleration response, then the piping system equations of motion are being analytically integrated correctly. For the piping system in this study, the maximum response of the 12.31 Hz mode, produced by the vertical earthquake shock, occurred 6.06 seconds after initiation of the seismic event. This time is identical to the time at which the maximum acceleration response was reached, at 12.3 Hz, when computing the response spectrum from the vertical earthquake excitation time history.

Besides comparing the maximum total structural responses of a piping system, the above comparative methods can not be used to compare Newmark-beta direct integration time history analysis results and response spectrum analysis results. Direct integration time history analysis results are not defined in terms of structural modes. The time history results must be transformed from the time domain into the frequency domain in order to compare them to response spectrum analysis results. A Fourier transformation program is used to perform the time domain to frequency domain conversion (7).

Provided there is sufficient seismic excitation energy, the effects of dominant piping modes can easily be seen in Fourier transforms of the piping response time histories. Figure 4 shows the Fourier transformation of the M_z reactor vessel nozzle moment response time history, along with the natural frequencies of the dominant pipe modes, which were calculated using the response spectrum method. There is good agreement between the frequencies of the Fourier transformation peaks (4.84 Hz, 7.92 Hz, 12.3 Hz) and the natural frequencies of the dominant pipe modes (4.82 Hz, 8.0 Hz, 8.2 Hz, 12.3 Hz). The difference in the frequencies near 8 Hz is due to the combined response of the 8.0 Hz and 8.2 hz piping modes in the direct integration time history analysis. The frequency difference is also due to the peak seismic excitation harmonic occurring at 7.92 Hz rather than between 8.0 Hz and 8.2 Hz. Because the structure responds at the forcing excitation frequency, the response of the 8.0 Hz and 8.2 Hz modes occurs at 7.92 Hz. If the difference is greater than 10 percent between the frequency of the forcing function harmonic and the frequency of the dominant pipe modes, for low levels of structural damping, an error exists in one or both of the dynamic analyses.

Errors in the direct integration time history analysis can be identified by comparing the frequencies of the input excitation peaks, calculated by performing a Fourier transformation of a seismic excitation time history, with the frequencies of the Fourier transformation peaks of the piping response time histories produced by the corresponding seismic excitation. The seismic excitation peak at 7.92 Hz and the corresponding piping response peak at 7.92 Hz, for the piping system in this study, were discussed in the previous paragraph. Another seismic excitation peak occurs at 16.3 Hz. The piping mode with the closest natural frequency to 16.3 Hz has a natural frequency of 17.7 Hz. The 17.7 Hz piping mode is one of the dominant piping modes, but there is not significant seismic excitation between 16.4 Hz and 18.0 Hz. The response of this pipe mode produces a peak at 16.3 Hz in the Fourier transform of the M_z reactor vessel nozzle moment, as shown in Figure 4. If the difference in frequency is greater than 5 percent between the Fourier transform peaks of the seismic excitation and the Fourier transform peaks of the piping response time histories, the direct integration time history analysis is in error.

CONCLUSIONS

A prototypic LMFBR piping system was subjected to a seismic event and its structural response calculated using the response spectrum analysis method and time history analysis methods. There was a large variance in the differences between the response spectrum analysis results and the time history analysis results. Some of the variance between the two sets of results is attributable to the different methods used in the analyses for combining the modal contributions to obtain the total structural response. The effects of the different modal combination methods can not be assessed before performing the time history analyses.

Part of the difference between the response spectrum analysis and time history analysis results can be identified before performing the time history analyses. Differences between the seismic excitation input used in the two analytical methods produces differences between the two sets of analytical results. Methods were presented in the paper to compare these differences between the seismic excitations used in the two types of dynamic analyses.

The complexity of piping systems, seismic excitation, and the interaction between them makes it difficult to verify that the calculated piping system is not in error. Methods presented in this paper can identify errors, if they exist, in the dynamic response of a piping system calculated using the response spectrum method or time history methods. As a result of the comparative procedures, confidence can be gained in the mathematical accuracy of piping system response produced by seismic excitation.

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TABLE 1

MAXIMUM REACTOR VESSEL NOZZLE LOADS CALCULATED USING TWO ANALYTICAL METHODS

Analytical Method	Nozzle Load F_x Kg	F_y Kg	F_z Kg	M_x Kg-m	M_y Kg-m	M_z Kg-m
Response Spectrum Analysis	8740	8470	8130	38500	94300	89100
Modal Superposition Time History Analysis	5080	6940	4720	32700	54400	78800
% Difference Between Methods	42	18	42	15	42	11

TABLE 2

MODAL CONTRIBUTION FROM 12.31 Hz MODE TO REACTOR VESSEL NOZZLE RESPONSE

Analytical Method	Nozzle Load F_x Kg	F_y Kg	F_z Kg	M_x Kg-m	M_y Kg-m	M_z Kg-m
Response Spectrum Analysis	1880	4420	99	990	900	39900
Modal Superposition Time History Analysis	1410	3330	75	750	680	30000
% Difference Between Methods	25	25	24	24	24	25

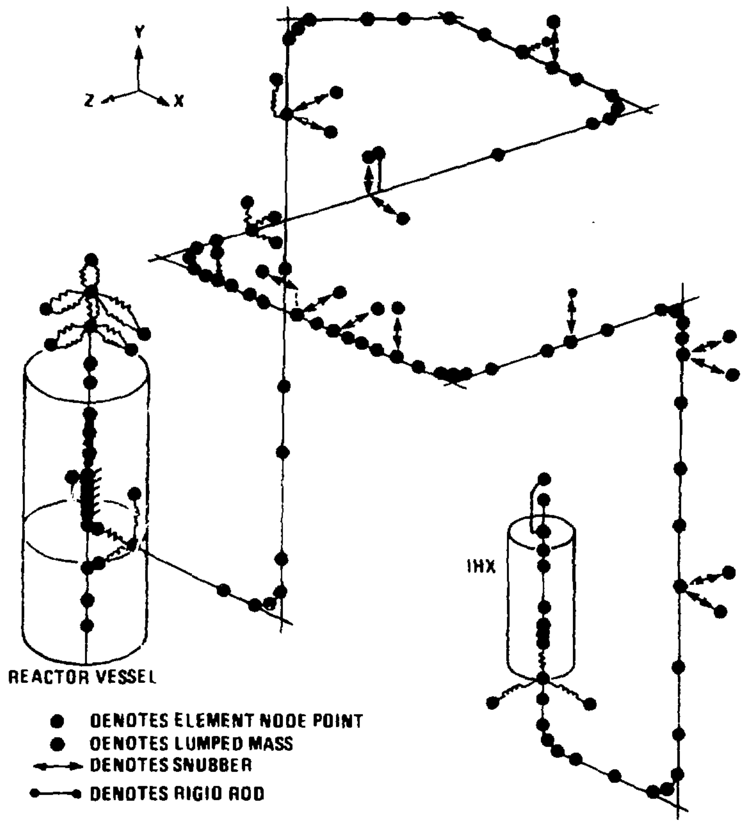

Figure 1. Idealization of Prototypic Piping Leg

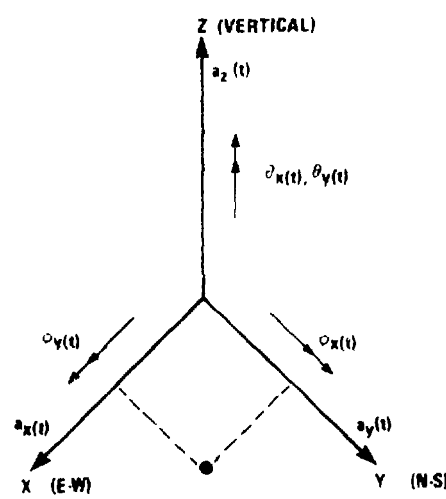

Figure 2. Coordinate System of the Earthquake Excitation

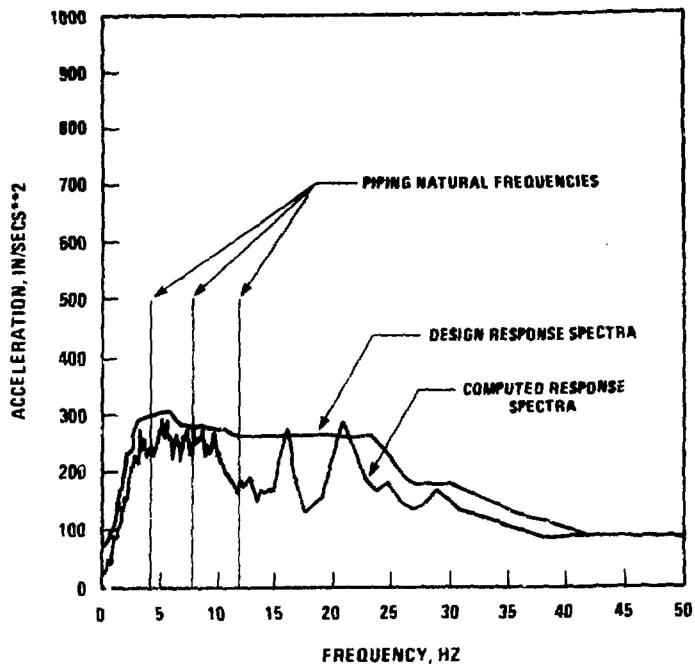

Figure 3. Comparison of Design Response Spectra and Computed Response Spectra of Vertical Earthquake Shock

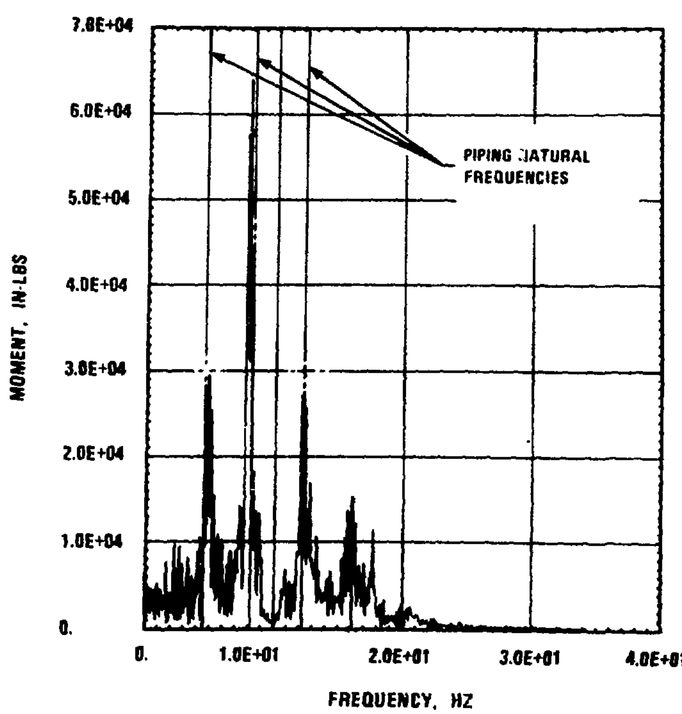

Figure 4. Natural Frequencies of Dominant Piping Modes Compared to Fourier Transform of Reactor Vessel Nozzle Response Time History