Review of the Validity of Random Phasing Rules as Applied to CO Torus Loads

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INTRODUCTION

The LDR [1] specification for CO Torus loads is based on FSTF data (primarily test M-8). In order to resolve potential uncertainties in the conservatism of the data, supplementary tests M-11B and M-12 were conducted in the FSTF facility. While M-12 was not totally bounded by the LDR specification, the staff felt that the LDR procedure of summing the absolute values of the harmonic components was sufficiently conservative to bound any uncertainties in the data (Supplement to Mark I SER-NUREG-0661).[2]

Many of the individual Mark I plants have chosen to deviate from the LDR procedure and have reduced the conservatism inherent in the absolute sum load application through some use of random phasing between harmonics of the LDR CO rigid-wall pressure specification. The basis for all of these alternate load application procedures comes from GE report NEDE-24840[3] and some subsequent reports by Structural Mechanic Associates (SMA 12101.04-RODID, SMA 12101.04-R002D, SMA 12101, 04-R003D).[4,5,6] While individual plants obtain a reduction in load due to the effect of random phasing in different matter, a generic evaluation of the base for these procedures is necessary in order to establish the adequacy of each plant's exception to the Acceptance Criteria.

A. Review of GE NEDE 24840, "Evaluation of Harmonic Phasing for Mark I Torus"

The primary objective of this report is to reduce the excessive conservatism in the torus shell response due to the use of the absolute sum of harmonic amplitudes. The report demonstrates, by examining through Monte Carlo calculation both the FSTF data and an actual facility (Oyster Creek), that random phasing leads to a more realistic response. The report further proposes a design rule that is relatively easy to apply and provides 90% confidence of 50% non-exceedance probability.

The report further justifies this choice as being appropriate to preserve, at the response level, the non-exceedance probability or the degree of conservatism contained within the load data. Seven responses (BDC axial and hoop stress, BDC radial displacement, and four column forces) at the FSTF facility are analyzed on three different bases: (a) Fourier components of the measured spatially-averaged pressure time histories over 5 (second) intervals of Run Number M-8 are used as load input; (b) Monte Carlo trials based on random phasing between the 50 harmonic components representing the histories in (a) are applied; (c) Monte Carlo trials using random phasing among the 50 harmonics of the LDR load specification are used. The peak responses resulting from theses analyses are then compared to the measured peaks in the FSTF tests.

A comparison of the results of (a) to the measured responses suggests that the modelling of the facility and a representation of the data is adequate to match the column forces and radial displacement but yields peak membrane stresses that are from 13% to 30% (hoop) too low. The report goes into a number of explanations for the reasons for this discrepancy. While most of the suggested causes would not be applicable in a real facility, the suggestion

that shell membrane stresses will respond to local pressures while the input load has been averaged, can be assumed to be transferable to a plant calculation. This potential non-conservatism is eventually recognized in the final design rule.

The peak responses at the 50% NEP level resulting from 200 Monte Carlo trials with random phasing between harmonics (option b) generally either bound the results using actual phasing or are very close to them. The ratio of the responses, based on (a) divided by the 50% NEP result of (b) ranges from 0.88 for the column forces to 1.03 for the radial displacement, with the membrane stresses at 0.94. The 50% NEP result of (b) comes closer to bounding the experimental data but the membrane stresses are still low (9% axial and 15% hoop).

The 200 Monte Carlo trials are also performed for the LDR specification. Because of some additional conservatisms in the load harmonic amplitudes, the 50% NEP now bounds the column forces and radial displacement substantially, essentially matches the axial membrane stress, and underpredicts the FSTF peak hoop stress by only about 6%.

The report then proceeds to perform 200 Monte Carlo response calculations for the model of a real facility (Oyster Creek). Clearly in this exercise only the LDR harmonics can reasonably be applied and no direct comparison to experiments can be performed. The results, however, suggest that the cumulative probability distributions (CDP's) for the real facility are very similar to those for the FSTF facility. The ratio of the 50% NEP level to the absolute sum is about the same as in FSTF and lies in the vicinity of 50% for the monitored responses. The report's subsequent discussion of the proper way to combine stresses is outside the scope of this review and not directly relevant to the load specification issue.

On the basis of the information summarized above, the report recommends a simple design rule that will yield 90% confidence of 50% NEP. The results of (b) and (c) for FSTF, and the calculations for Oyster Creek demonstrate that taking an absolute sum of the three highest harmonics (at response level) coupled to a square root of the sum of the squares (SRSS) of the remaining harmonics always bounds and closely approximates the 50% NEP level. The report, therefore, suggests the use of this simple algorithm for the addition of the harmonic components in the frequency domain. In order to provide additional conservatism in a real facility, the harmonic load components that span a structural natural frequency are tuned to the natural frequency rather than applied at the average frequency in the interval. A comparison of the application of this design rule to the FSTF facility (where frequency tuning is not used) to the measured data shows that all peak responses are bound, except the hoop stress which is about 5% low. The report suggests a number of conservatisms in the loading that would compensate for this small discrepancy. The primary effect suggested is related to the damping of 2% used in analysis. In a real facility, where loads are combined and are thus higher, the 2% damping is a conservative representation of the structure and would thus lead to conservative responses.

B. Review of SMA report 12101.04-R001D, R002D and R003D

Report SMA 12101.04-R001D, "Evaluation of FSTF tests M12 and M11B Condensation Loads and Responses," was not available and thus not directly reviewed. The major results and conclusions of that report are, however, summarized in SMA 12101.04R002D, and were found to be consistent with both the original report NEDE-24840 and the FSTF Supplemental Test Letter Report M1-LR-81-01P.

Report SMA 12101.04-R002D, "Response Factors Appropriate for Use with CO Harmonic Response Combination Design Rules," summarizes all of the conclusion of NEDE-24820 and updates the comparison to include FSTF tests M12 and M11B. When test M12 is included in the comparison, the design rule application of the LDR harmonics to the FSTF torus underestimates peak measured membrane axial stress by 11% and underestimates the hoop stress by 14%, while bounding the other responses. On the basis of this comparison, the report suggests modifying the design rule by using a "response factor: $R_f = 1.0$ for other responses. In addition, the report adds an additional design rule for those circumstances where the combination of absolute sum and SRSS is not convenient, such as in the time domain. In this case the report states that a 90% confidence of 50% NEP level can be achieved by multiplying the peak response resulting from a single random phased trial by 1.15. Note that for membrane stresses and strains there is an additional 1.15 "response factor" described above. The conclusions provide criteria for design analyses along the lines just discussed, but an additional simplification of neglecting harmonic components above 30 HZ is suggested for structures with similar natural frequency content to the FSTF or Oyster Creek.

Report SMA 12101.04-R003D, "Statistical Basis for Load Factors Appropriate for Use with CO Harmonic Response Combination Rules," reiterates the design rules described above. In addition, recognizing potential uncertainties in the data, the report attempts to provide some justification for neglecting any additional factor to provide adequate conservatism. The report shows that, considering the specification is a result of three data points (M8, M12, M11B), the increase in response to achieve 75% confidence of 84% NEP ranges from 2% for inside column force to 33% for the hoop stress. The report further quotes an unreferenced communication from Dr. Alan Bilanin as stating a factor of 1.33 for the ratio of the FSTF data to that expected in a real full torus. This effect is purported to be the result of the rigid end effects, but no further explanation is provided. In Appendix A, this effect is examined. We conclude that for these frequencies that are not correlated between bays, the FSTF should produce 32% to 35% higher loads than would exist in a real facility. An examination of the FSTF data (in Supplemented Letter Report M1-LR-81-01-P) shows that only the fundamental frequency near 6 Hz shows any correlation between downcomers. If one assumes correlation between bays at that frequency and random phasing between bays at all other frequencies, the overall conservatism for the average pressure may be as low as 17%, while at the response level the FSTF conservatism will range form 18% for the hoop stress to 38% for the axial stress. If we now balance this versus the maximum expected uncertainty factor for hoop stress (1.33) as in report R003D, we could expect a

maximum degree of nonconservatism of about 13%. This is not serious for two distinct reasons. The additional conservatisms associated with the real structure due to the tuning of harmonic components to the natural frequencies and the closer match to the 2% damping factor can easily compensate for the slight nonconservatism. Secondly, the uncertainty estimate, using only three peak responses form the tests M8, M11B and M12 is probably excessively conservative. If one used 1 second averaged RMS pressures from 8-second high mass flow intervals, as was done in the SER Supplement, the ratio of mean to peak R = 0.72 and the standard deviation is $\sigma_r = 0.172$. The resultant load or response at $2\sigma_r$ from the mean (now providing a very high confidence level of non-exceedence) is only 7% above the design rule and can be easily compensated by the 1.18 conservatism factor for the FSTF.

C. Summary and Conclusions

On the basis of the review of these reports the staff concludes that a direct application of design rules as given in report SMA 12101.04R002D on page 41 or in report SMA 12101.04-R003D on pages 1-2 is acceptable. If harmonics above 30 Hz are neglected, as suggested for structures similar to FSTF or Oyster Creek, a specific justification in the form torus response frequency characteristic must be presented.

Any variation that produces at least as high a ratio of response to that produced by absolute sum as the highest observed in the FSTF and Oyster Creek analyses (63%) is also acceptable. Using the design rule as initially stated on NEDE-24840 (without the 1.15 factor for shell stresses) is not acceptable, but a modification using 4 harmonics summed absolutely added to the remaining summed SRSS is marginally acceptable, provided the reported shell stresses are not within a few percent of allowables. The addition of 1 harmonic, to be summed absolutely, provides only about a 10% increase in the responses rather than the 15% needed to bound FSTF measurements. The effect is sufficiently small, however, that further evaluation would be necessary only in the event the resultant stresses approached allowable values very closely.

In summary, the staff finds the analysis presented in the series of reports reasonable. Any conservative application of those results is thus acceptable. The direct application of the design rules, as stated in the final report SMA 12101-04-R003D is considered adequately conservative. Any alternate is acceptable, provided its application to FSTF data would bound all the measured stresses.

APPENDIX C

THE DESCRIBING EQUATIONS FOR THE BNL METHOD OF IMAGES

METHOD OF IMAGES

1. By the method of images, the image locations are defined by

$x_i = 2L_i \pm x_o$ $\quad$ i, j, k = 0, ±1, ±2 ...
$y_j = 2H_j \pm y_o$
$z_k = 2D_k \pm z_o$

The tank dimensions are L, H, D in the x, y and z direction respectively. y is the vertical direction, y = 0 is the tank bottom and y = H is the free surface. The origin of the coordinate system is at the lower left corner. x_o, y_o, and z_o define the location of the source with strength P_o.

The potential at any point (x, y, z) can be expressed as

$$P = \sum_i \sum_j \sum_k \frac{(-1)^j P_o}{\sqrt{(x_i-x)^2 + (y_j-y)^2 + (z_k-z)^2}}$$

Define

$\xi_1 = x_0 - x$, $\xi_2 = -x_0 - x$, $\xi_3 = -x_o + x$, $\xi_4 = x_0 + x$
$\eta_1 = -y_0 + y$, $\eta_2 = 2H - y_0 - y$, $\eta_3 = y_0 + y$, $\eta_4 = 2H + y_0 - y$
$\zeta_1 = z_o - z$, $\zeta_2 = -z_0 - z$, $\zeta_3 = -z_0 - z$, $\zeta_4 = z_0 + z$

and

$$I^{+}_{ijklmn} = \frac{1}{\sqrt{(2L_i+\xi_l)^2+(4H_j+\eta_m)^2+(2D_k+\zeta_n)^2}}$$

$$I^{-}_{ijklmn} = \frac{1}{\sqrt{(2L_i+\xi_l)^2+(4H_j+2H+\eta_m)^2+(2D_k+\zeta_n)^2}}$$

so that

$$P = P_o \sum_{k=0}^{N} \sum_{h=1}^{NK} \sum_{i=0}^{L} \sum_{l=1}^{NI} \left\{ \left[\sum_{j=0}^{M} \sum_{m=1}^{4} \left(I_{ijklmn}^{+} - I_{ijklmn}^{-} \right) (-1)^{m+1} \right] + I_{i,M+1,k,l,1,n}^{+} - I_{i,M+1,k,l,2,n}^{+} \right\}$$

where

NI = 4	if	$i \neq 1$
NI = 2	if	$i = 1$
NK = 4	if	$k \neq 1$
NK = 2	if	$k = 1$

and L, M and N define the number of images used in the image array.

APPENDIX D

THE NRC REQUEST FOR ADDITIONAL INFORMATION AND THE NMPC RESPONSE