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ON THE USE OF MATERIAL-DEPENDENT DAMPING IN ANSYS FOR MODE SUPERPOSITION TRANSIENT ANALYSIS

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ABSTRACT

The mode superposition method is often used for dynamic analysis of complex structures, such as the seismic Category I structures in nuclear power plants, in place of the less efficient full method, which uses the full system matrices for calculation of the transient responses. In such applications, specification of material-dependent damping is usually desirable because complex structures can consist of multiple types of materials that may have different energy dissipation capabilities. A recent review of the ANSYS manual for several releases found that the use of material-dependent damping is not clearly explained for performing a mode superposition transient dynamic analysis. This paper includes several mode superposition transient dynamic analyses using different ways to specify damping in ANSYS, in order to determine how material-dependent damping can be specified conveniently in a mode superposition transient dynamic analysis.

INTRODUCTION

The commercial finite element software ANSYS has been widely used in the nuclear industry for analysis and design of structures, systems, and components (SSCs) in nuclear power plants (NPPs). In particular, it has been applied in various ways to the area of seismic analysis and design, in which damping is one of the critical factors to properly characterize the dynamic responses of a structure. All transient dynamic structural analysis methods in ANSYS require an appropriate specification of damping in order to simulate energy dissipation within the structure. For complex structures, such as the seismic Category I structures in NPPs, that can consist of multiple materials, each type of material may have a different energy dissipation capability and thus may require a different damping value. To this end, ANSYS has the capability to specify material-dependent damping. Facilitated with the increased capability of modern computer technology, complex structures can nowadays be modeled to greater details than in the past and consequently result in larger computational models. Therefore, the mode superposition method remains to be a very valuable tool for transient dynamic analyses of the large structural models, and is available in ANSYS. The mode superposition method is faster and less expensive than the full method and the reduced method, which are the other two solution methods provided in ANSYS for transient dynamic analysis [1].

A recent review of ANSYS manuals for several releases found that the specification of material-dependent damping is not clearly defined for the mode superposition transient analysis. An ANSYS user who is less experienced in utilizing material-dependent damping and the mode superposition method for transient dynamic analyses could end up with a structural model of zero damping. Although a non-damped structural system can usually be detected without much difficulty by examining the dynamic responses, it requires experience and discipline for one to perform the necessary examination, identify the cause, and find the correct solution.

This paper is aimed at determining how material-dependent damping can be specified conveniently in ANSYS in a mode superposition transient dynamic analysis. A simple cantilever beam is analyzed using various damping options in ANSYS. The discussion in this paper is primarily based on ANSYS Release 10 [1]. It is noted that the most recent release is ANSYS Release 13 [6].

Wherever ambiguity does not occur hereinafter, *the manual* refers to the manual of ANSYS Release 10 (similarly

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for *theory manual*, *user manual*, etc), and capitalized words refer to ANSYS commands.

THE CONVENIENT COMBINATION

Per the manual, Structural Guide, Section 5.4 "Performing a Mode Superposition Transient Dynamic Analysis," the procedure for a mode superposition transient analysis includes three major steps: (1) modal analysis, (2) mode superposition analysis, and (3) expansion for results. In the modal analysis, the default mode-extraction method is the Block Lanczos method; other mode-extraction methods applicable to the mode superposition method are the reduced, subspace, PowerDynamics, or QR damped methods. The Block Lanczos method is capable of finding many modes of large models and requires a medium amount of memory and low disk space. It performs well when the model consists of shell elements or a combination of shell and solid elements. In particular, this method is recommended for models of poorly shaped solid and shell elements.

As previously noted, material-dependent damping is preferable for complex structures having multiple materials. Moreover, material-dependent damping ratios have particular advantage over other damping specifications such as alpha damping and beta damping, because (1) recommended damping ratios are available in standards and codes for typical materials and components, and (2) unlike alpha damping and beta damping, specification of damping ratios do not require the identification of dominant modes for those materials and components, which can be a difficult task if the subject structure is complex.

Therefore, a combination of the Block Lanczos method and specification of material-dependent damping ratios becomes a convenient method for mode superposition transient dynamic analysis.

MATERIAL-DEPENDENT DAMPING FOR THE MODE SUPERPOSITION METHOD

Per the theory manual, Section 15.9, "Mode Superposition Method," the mode superposition method using Lanczos and subspace extraction methods allows only Rayleigh (ALPHAD or BETAD) or constant damping (DMPRAT), so that the damping matrix *C* in the equations of motion can satisfy the orthogonal condition like the mass matrix *M* and the stiffness matrix *K*, i.e.:

$$\{\phi_j\}^T[C]\{\phi_i\} = 0 \quad \text{for} \quad i \neq j \tag{1}$$

Subsequently, the damping ratio ξ_j for mode j is expressed as:

$$\xi_j = \frac{\alpha}{2\omega_j} + \frac{\beta\omega_j}{2} + \xi + \xi_j^m \ , \tag{2}$$

in which

- α: uniform mass damping multiplier (ALPHAD),
- β: uniform stiffness damping multiplier (BETAD),
- ξ: constant damping ratio (DMPRAT)
- ξ_j^m: modal damping ratio (MDAMP)

The modal damping ratio is a supplement to the Rayleigh damping and the constant damping ratio, which are permitted in Eq. (1). The theory manual also states that the constant stiffness matrix multiplier β^m (MP,DAMP) and constant material damping coefficients β^ξ (MP,DMPR) are not applicable in modal damping. Structural Guide of the manual indicates that the MP,DAMP command can specify two types of material-dependent damping: beta damping (β) or damping ratio ξ (for a spectrum analysis). So, it was not immediately clear whether MP,DAMP indicates a beta damping or a damping ratio when it is used in a mode superposition analysis.

CONFIRMATORY ANALYSIS

A number of confirmatory analyses were carried out to investigate this combination. A simple vertical cantilever beam with a concentrated mass at the top was created in ANSYS for this investigation. Only one material type was assumed in this model, in order to use other ANSYS damping options to benchmark the subject problem. However, the findings will be equally applicable to structures with multiple material types. To simulate a seismic wave at the base, a force time history was applied to an extremely large mass that was attached at the base, effectively creating an input of acceleration time history. A 5% damping ratio was assumed for the beam. Other details of the model, including the units, are not important to the discussion and are omitted for brevity. The relative displacement at the top, with respect to the base, is used for comparison.

The calculation procedure was adapted from the "Sample Input for a Mode Superposition Transient Dynamic Analysis," which can be found at the end of the Structural Guide of the manual. Since this procedure will be adapted later for other analyses, the major commands are shown in the following list to demonstrate the three steps for a mode superposition transient dynamic analysis.

MD,DAMP is not shown in the following list because it was specified during model creation.

SAMPLE COMMAND LISTING FOR MODE SUPERPOSITION TRANSIENT ANALYSIS

```
!  Step (1): Modal Analysis
/SOLU
ANTYPE,MODAL          ! Modal analysis
MODOPT,LANB,...       ! Block Lanczos
   ! A MYSTERY COMMENT LINE
SOLVE
FINISH

! Step (2): Mode Superposition Ana.
/SOLU          ! Reenter SOLUTION
ANTYPE,TRANS   ! Transient analysis
TRNOPT,MSUP,...! Mode superposition
MDAMP,...      ! Modal damping ratios
LSWRITE        ! Write first load step
---
---! Loads, etc. for 2nd load step
TIME,...       ! end of 2nd load step
LSWRITE        ! Write 2nd load step
SAVE
LSSOLVE        ! solution
FINISH

! Step (3): Expand the Solution
/SOLU          ! Reenter SOLUTION
EXPASS,ON      ! Expansion pass
OUTRES,...     ! Results output
SOLVE
FINISH
```

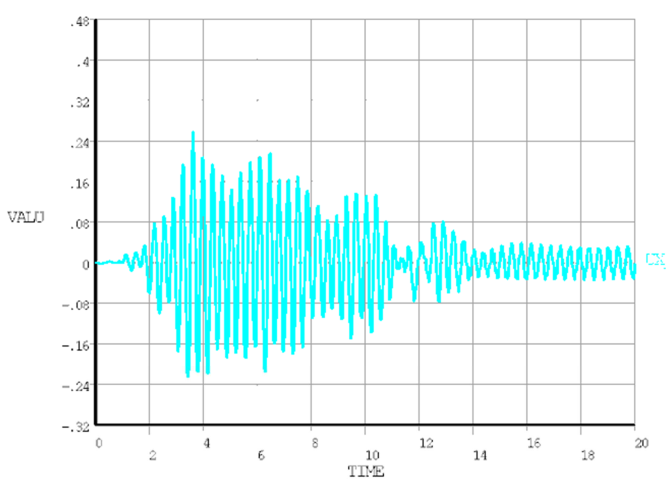

FIGURE 1 MP,DAMP=0.05 AND BLOCK LANCZOS

Figure 1 shows the relative displacement at the top of the cantilever beam. Although the overall shape of the displacement response somewhat resembles a seismic displacement response, it appears to cycle more than expected for a 5% damped system. In particular, the displacement does not ramp down to zero at the end. It is therefore suspected whether the specified damping has been applied correctly.

As a parametric study, a zero value was specified at the MP,DAMP command to confirm whether the previous analysis has an effect of damping. Figure 2 shows the relative displacement at the top, obtained by intentionally assigning a zero damping in the model. Figures 1 and 2 are identical and the MD,DAMP command appears to be ignored in both cases.

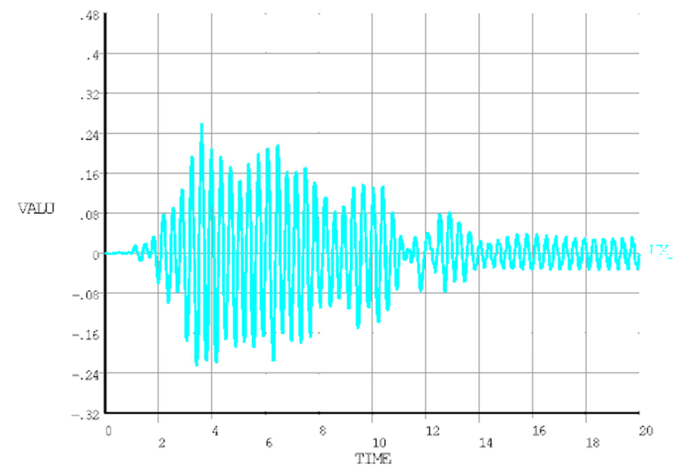

FIGURE 2 MP,DAMP=0.0 AND BLOCK LANCZOS

The QR damped mode-extraction method requires a form of damping to be specified in the model creation or in the modal analysis. On the other hand, the Block Lanczos method, as well as most of the other mode-extraction methods, does not require a form of damping in the modal analysis as expected. The damping specification in conjunction of the Block Lanczos method is therefore believed to occur in the mode superposition analysis (Step 2), as also indicated by Eq. 2. This belief agrees with what has been shown in Figures 1 and 2, i.e., MP,DAMP is ignored.

To further confirm this finding, the same analyses, corresponding to the 5% and 0% damping ratios, were re-analyzed using the QR damped mode-extraction method. Figures 3 and 4 show the relative displacement obtained at the top. Figure 4 is identical to Figures 1 and 2, because the damping value was intentionally set to zero. Figure 3 appears to be a result of a damped system, in particular the displacement ramps down to zero at the end of the analysis. However, the displacement result shown in Figure 3 may not be correct, because the damping value expected by the MP,DAMP command can be either beta damping or the damping ratio. As previously pointed out, the manual indicates that MP,DAMP damping is damping ratio for the spectrum analysis. These two analyses show that MP,DAMP command is honored by the QR damped mode-extraction method.

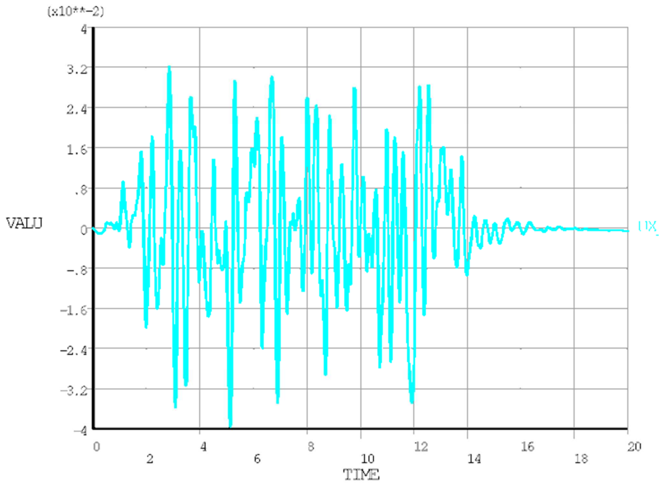

FIGURE 3 MP,DAMP=0.05 AND QR DAMPED

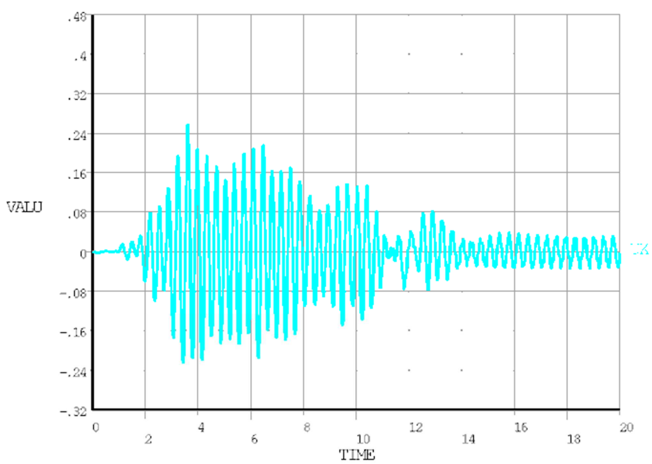

FIGURE 4 MP,DAMP=0.0 AND QR DAMPED

THE CORRECT DISPLACEMENT RESPONSE

As shown in Eq. 2, a constant damping ratio (DMPRAT) can be specified in ANSYS for all modes. For the sample problem with only one material, a material-dependent damping ratio can be achieved through DMPRAT. Therefore, the cantilever beam model was modified to use the DMPRAT command, in conjunction with the Block Lanczos method. The goal was to obtain a benchmark displacement result for comparison. The same damping values (5% and 0%) as used in the first two cases were used to generate Figures 5 and 6.

Figure 6 is identical to Figures 1, 2, and 4, confirming that the displacement histories shown in Figures 1, 2, and 4 are truly responses of undamped systems.

Figure 5 is a typical response of a lightly damped system subjected to a seismic input motion. The displacement cycles in the pace of the fundamental frequency of the beam but also resembles the shape of the seismic input motion because of proper damping. The displacement ramps down to zero at the end of the analysis. This figure is obviously different from Figure 3, indicating that the MP,DAMP command associated with the QR damped mode-extraction method is translated to beta damping, although it was set to 0.05 numerically in that analysis.

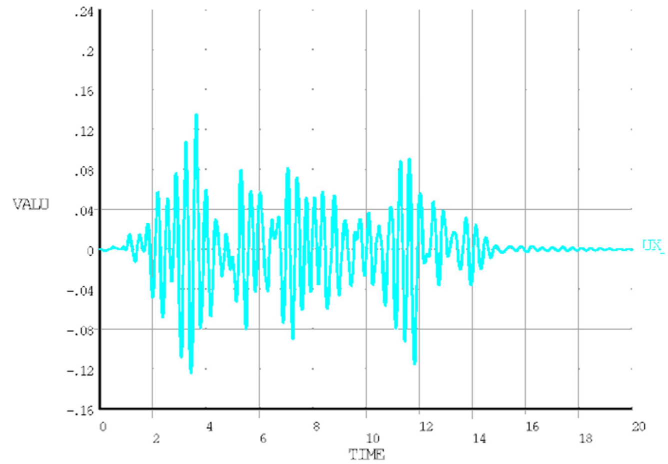

FIGURE 5 DMPRAT=0.05 AND BLOCK LANCZOS

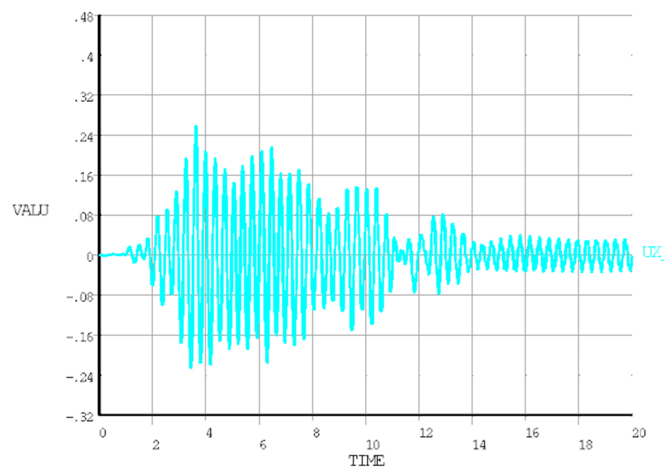

FIGURE 6 DMPRAT=0.0 AND BLOCK LANCZOS

THE CONVENIENT COMBINATION FOR CORRECT DAMPING

So far, the confirmatory analyses have not been able to show that the MP,DAMP command is translated to either a beta damping or a damping ratio, when it is used in a mode superposition transient dynamic analysis. But, it tends to indicate that such a convenient combination (MP,DAMP +

Block Lanczos) may lead to zero damping. ANSYS is a mature and traditional code for structural analysis; missing such a feature in ANSYS is quite unlikely. Therefore, further investigation was performed to this end.

In Section 5.9 of the manual, “Transient Dynamic Analysis Options,” Table 5.5, “Damping for Different Analysis Types,” shows that material-dependent damping MP,DAMP is available to the mode superposition transient analysis, with two footnotes for further qualification. Footnote 6 refers to the QR damped mode-extraction method, which was investigated in this paper and concluded to be correct. Footnote 4 reads, “if converted to modal damping by expansion of modes.” Unfortunately, this footnote is less instructional regarding how expansion of modes converts the material-dependent damping ratio to modal damping, and neither is the description of the mode expansion command EXPAND.

During the process of investigation, Reference 2, “Accounting for Damping in ANSYS,” became available to one of the authors and explained how to achieve proper damping using this convenient combination. More recently, the current ANSYS Release 13 explains more clearly on this aspect.

According to ANSYS Release 13 theory manual, the modal damping ratio ξ_j^m for mode j can be either defined directly using the MDAMP command or alternatively by converting from the material-dependent damping (MP,DAMP). In this case, MP,DAMP is interpreted as damping ratio rather than the beta damping (stiffness matrix multiplier). Since MDAMP occurs in Step 2 as shown in the sample listing while the MP,DAMP occurs before Step 1 (in model creation), any manually specified modal damping through MDAMP will overwrite those converted from MP,DAMP.

To convert MP,DAMP to modal damping, an effective mode-dependent damping ratio is defined based on the ratio of strain energy in each material in each mode, i.e.:

$$\xi_j^m = \frac{\sum_{m=1}^{M} \xi_m E_m^s}{\sum_{m=1}^{M} E_m^s}, \tag{3}$$

where M is the total number of materials, ξ_m is the material-dependent damping ratio specified by the MP,DAMP command, and E_m^s is the modal strain energy for material m. The modal strain energy is defined by,

$$E_m^s = \frac{1}{2}\left\{\varphi_j\right\}^T [K_m]\{\varphi_j\}, \tag{4}$$

in which $\{\varphi_j\}$ is the displacement mode shape for mode j.

The calculation of these effective mode-dependent and material-dependent damping ratios ξ_j^m occurs in the modal analysis (Step 1) and is then carried over to the subsequent mode superposition transient dynamic analysis or spectrum analysis. The key command to trigger this calculation is MXPAND,,,,YES, which should be inserted in Step 1, for example, at the location indicated by the “A MYSTERY COMMENT LINE” in the sample command listing. The option “Yes” is significant in this analysis, in order for the mode expansion command to include calculation of element “stresses”, which in a modal analysis are not the actual stresses in the model but represent a relative stress distribution for each mode.

To confirm what has been learned, a case with MP,DAMP=0.05, the Block Lanczos mode-extraction method, and MXPAND,,,,YES, was analyzed and the relative displacement at the top is shown in Figure 7. It clearly agrees with Figure 5, the correct result obtained using a constant damping ratio (DMPRAT). Therefore, MXPAND,,,,YES is the necessary condition for the convenient combination to achieve a proper damping.

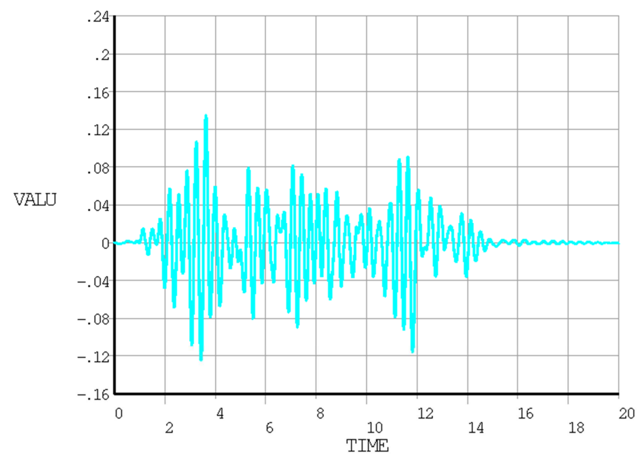

FIGURE 7 MP,DAMP=0.05, BLOCK LANCZOS, AND MXPAND,,,,YES

In fact, MXPAND,,,,YES is found in the default “Sample Inputs for a Mode Superposition Transient Dynamic Analysis,” in Release 13 as well as in Release 12.1 [5], but not in some prior releases [1, 3, 4]. So, if these two samples are used as a basis for adaption, it is less likely to result in a zero-damping.

SUMMARY

This paper explores whether the material-dependent damping ratio (MP,DAMP) and the Block Lanczos mode-extraction method in ANSYS can be used as a convenient combination to achieve proper damping for complex structures that may have multiple types of materials. It concludes that the mode expansion command MXPAND,,,,YES is a crucial command for this convenient combination to introduce damping properly. This paper also finds that the most recent ANSYS Release 13 documents this feature in a much clearer fashion than the prior releases. For users who use Release 12.1 or some other earlier releases, this paper provides useful clarifications and can serve as a guidance on the appropriate application of the material-dependent damping ratio (MP,DAMP) and the Block Lanczos mode-extraction method in a mode superposition transient dynamic analysis.

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