A STAND-ALONE DMAP PROGRAM FOR MODAL CROSS-CORRELATION

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ABSTRACT

A standalone DMAP program has been developed which gives the MSC/NASTRAN analyst a more complete set of tools with which to address the task of modal cross-correlation analysis. This program brings a number of user-oriented features to the otherwise fairly simple $[\phi]^T[M][\phi]$ calculations. These features include options for reducing and realigning the DOFs between the two models (manual or automatic), re-ordering and/or removing modes, and several normalizing and filtering options. The program has been tested and used with both simple test models and real-world models. The paper briefly explains modal cross correlation and discusses the tools that this DMAP brings for both pre-processing of the input matrices and post-processing of the results.

A Stand-alone DMAP Program for Modal Cross-Correlation

The intent of this paper is to describe a standalone DMAP program that gives the MSC/NASTRAN analyst additional tools with which to compare the dynamic behavior of two different models through modal cross-correlation. These tools are in addition to the current DMAP alter package that is available in the SSSALTER library delivered with MSC/NASTRAN (see the "postmac" files). This stand-alone DMAP program, herein named "XCORR", offers a number of additional user-oriented features to the simple $[\phi_1]^T[M_1][\phi_2]$ modal cross-correlation calculation. While the calculation itself is not that difficult, there is a lot of work that needs to be done in the preparation of the $[\phi_i]$ matrices: insuring there are the same number of DOF in each matrix, that those DOFs match up, placing both in the same coordinate system, insuring that both matrices have the same number of modes in the same order, etc. There are also output considerations: normalizing and/or filtering the resultant cross-correlation matrix in a way that will be most useful to the analyst in determining the how well the modes correlate.

The XCORR routine was initially developed in response to a user's request for help in re-ordering the DOF in the mode shape matrices. The initial program has since been expanded and many additional user-oriented features have been added in response to real-world considerations that have come up in its use.

This paper serves as expanded documentation for the features available in the XCORR routine, first briefly explaining modal cross-correlation and the interpretation of the cross-correlation matrix, and then moving on to describe the input data preparation features. The specific tools available in the XCORR solution sequence will be discussed as the topics come up throughout the paper. A more detailed description of the specific user inputs may be found in the DMAP listing for XCORR itself. If the explanations presented below are insufficient, the reader is referred to the DMAP listing for XCORR for more details. XCORR is extensively self-documented with approximately half the lines being comment lines, and several hundred DMAP MESSAGE statements. Extensive checks on the user's input (checking sizes, validity of input, etc.) are made whenever possible with comprehensible error messages should anything be awry.

Due to the length of the DMAP program presented (over 3500 lines at last count, including some 1800 comment lines and over 400 MESSAGE statements), the actual DMAP program cannot be presented herein, but is available through either Jack Scanlon at Analex (216) 977-0032 or Jim Swan at MSC (1-800-638-4672 or jim.swan@macsch.com). It should also be available in the SSSALTER library files supplied with MSC/NASTRAN, starting with V68.2.

Modal Cross-Correlation: How and Why

Modal cross-correlation is a technique that aids the analyst in determining if the modes from two different models share the same dynamic characteristics. It is based on a unique feature of modal analysis, namely that the calculation $[\phi]^T[M][\phi]$ yields a diagonal matrix. If the two $[\phi]$ matrices come from different sources, then a measure of how well they compare dynamically would be how close they come to forming a diagonal matrix when put into this equation. Differing $[\phi]$ matrices might come from two differently meshed MSC/NASTRAN models, or from models created by two different companies, or one set of mode shapes might be derived from test results or some other external analysis. In any case, if the dynamic characteristics of two different models are to be compared, then, as a minimum, modal cross-correlation should be performed.

Results Interpretation; Normalization and Filtering

An identical pair of mode shape matrices would give you a perfectly diagonal resultant $[\phi_1]^T[M_1][\phi_2]$ matrix. A less-than-perfectly correlated set of modes would start to generate off-diagonal terms in the resultant matrix. Completely unrelated sets of mode shapes would generate a fully-populated matrix with no discernible topology.

The task for the analyst is to see if there is some sort of recognizable topology to the cross-correlation matrix.

Recall that in general it is the *relative* displacements that are important in a mode shape, and not the absolute magnitude of the displacement. Similarly, it is the relative magnitudes (as compared to the off-diagonal terms) of the $[\phi_1]^T[M_1][\phi_2]$ resultant matrix that are usually the most important, and not the individual values. Since mode shape matrices may be arbitrarily scaled, the terms in the

$[\phi_1]^T[M_1][\phi_2]$ resultant matrix will be also. Hence, results interpretation generally will require some sort of normalization, and optionally, filtration of the resultant matrix.

One normalization technique would be simple normalization (divide every term by the largest term in the matrix). However, if the methods of eigenvalue normalization are different between the primary ($[\phi_1]$) and secondary ($[\phi_2]$) matrices, then simple normalization of the $[\phi_1]^T[M_1][\phi_2]$ matrix may not be sufficient. An alternative is to (re)mass-normalize both mode shape matrices, i.e. adjust the scale factors for each mode such that $[\phi_i]^T[M_1][\phi_i] = [I]$. Then at least there is somewhat consistent scaling factors between the two mode shape matrices and further normalization and filtering won't washout the resultant matrix topology. Successful mass normalization of the secondary mode shape matrix against the primary model's mass matrix will depend on how close the $[\phi_2]^T[M_1][\phi_2]$ calculation comes to forming a diagonal matrix - with a really bad set of secondary model modes, mass normalization of these modes may not be possible.

The XCORR DMAP program provides the analyst with either, both, or neither normalization technique. The first output from the XCORR solution sequence is the "raw", as-is $[\phi_1]^T[M_1][\phi_2]$ matrix. This matrix will always be printed. The user controls the type of subsequent normalization via user input PARAMeter NORML. The default value for NORML is "MAX", which just does simple normalization. Optionally, NORML can be set to "MASS" if the mode shapes are to be mass-normalized against the primary model's mass matrix, "BOTH", if both options are desired, or "NONE" if neither is desired. If the user chooses the "MASS" normalization option and the secondary model mode shapes cannot be successfully mass normalized, then XCORR will give the user appropriate warning messages and proceed on the secondary mode shape matrix as received. The user may also suppress the printout of terms smaller than the user-specified PARAMeter XCFILTER. Terms smaller in magnitude than XCFILTER in the normalized (any method) matrix will not be printed. The default value for XCFILTER is 0.0, i.e. no filtering at all. Information describing the normalizing and filtering options, if any, are printed out prior to printing any of the cross-correlation output matrices.

On Paper vs. In Practice: Input Preparation Tools

The theory and calculation of the modal cross-correlation matrix are relatively straightforward. For the user, most of the headaches will come in the preparation of the $[\phi_i]$ matrices. Ultimately there must be two identically sized $[\phi]$ matrices. Each row of the $[\phi]$ matrices must represent the same physical DOF of the actual structure. Each column in the $[\phi]$ matrices must represent the same mode. But what happens if there are different number of GRIDs or DOFs in the two sets of mode shape matrices? What if the GRID IDs don't match? What about different coordinate systems? Have the models been re-sequenced? What if one model has more modes than the other? What if the modes are arranged in different order? Are matrices to be brought in via database, DMIGs, or OUTPUT4 files? What if the analyst wants to compare a set of component modes from an upstream superelement? There is a lot more work to be done on the front end pre-processing the $[\phi_i]$ matrices than on the back end interpreting the results. The tools available in XCORR were developed to handle these pre-processing problems.

Step One: Bringing in the Matrices

Implicit in the modal cross-correlation calculation $[\phi_1]^T[M_1][\phi_2]$ is that the first two matrices come from one model, and the third matrix comes from another source. For purposes of discussion, the "1" model will be designated as the "primary" model and the "2" as the "secondary" one.

As a minimum, the analyst must therefore supply these three matrices, two from the primary model and one from the secondary model, to XCORR. The mode shape and mass matrices of the primary model must be obtained from an MSC/NASTRAN database via a DBLOCATE statement. The DMAP listing for XCORR shows the specific format for such a DBLOCATE request. The user will note that there are many other datablocks listed in that DBLOCATE statement, well beyond just the mass and mode shape datablocks. These extra datablocks are used if and only if additional user options in the preparation of the $[\phi_1]$ matrix are invoked.

The mode shape matrix from the secondary model may be brought in from either an MSC/NASTRAN database, an OUTPUT4 file (binary or BCD), or DMI bulk data entries. Again the user is directed to the actual DMAP listing for XCORR for the specific FMS statements and bulk data PARAMeters (see PARAMs EXTMODES, EXTUNITI, and/or EXTASCII) that may be required for of these input strategies. If the secondary model matrices are brought in through OUTPUT4 or DMI entries, the analyst will need to include enough GRID and/or SPOINT bulk data entries in the XCORR run so that the total number of DOFs match the number of rows in the secondary model's mode shape matrix. . These GRIDs/SPOINTs are mapped onto the rows of the secondary model mode shape matrix in ascending GRID/SPOINT ID order. The assigning of the rows of $[\phi_2]$ to GRIDs gives XCORR the necessary information to perform coordinate system transformations (based on the CD displacement coordinate system used on those GRIDs) and convenient labels for identifying which rows (DOFs) to filter out (more on both of these subjects later).

Now that the data from the primary and secondary models have be made available to XCORR, the analyst can start to massage them to get them into the proper size and order.

Step Two: Identify Superelement ID (if necessary)

This step is only necessary if either (or both) of the mode shape matrices to be compared happen to be component modes of an upstream superelement. If so, the user should let XCORR know which superelement is being used through the use of PARAMeters SEID1 and SEID2 to identify the superelement in question (e.g. PARAM, SEID1, 200 instructs the program to use the component modes from superelement 200 as the primary model modes). The default value for both SEID1 and SEID2 is 0, indicating both come from the residual structure.

Step Three: Coordinate Systems and Resequencing

The next task for XCORR is to transform the matrices into a consistent coordinate system and into a consistent DOF sort order. Most of this happens behind-the-scenes and requires no input from the user. The mass matrix and mode shape matrices (both primary and secondary) are transformed back to the BASIC coordinate system (CID=0) by default. If for some reason the user does NOT want this transformation to occur, then PARAMeter CORDX4M, NO should be included in the bulk data section. Coordinate system transformation is performed even if the secondary model information is brought in via OUTPUT4 or DMI bulk data entries. For both models, the transformations will be driven by the displacement coordinate systems (CD) in field 7 of the GRIDs associated with the respective model (primary and secondary). Necessarily, it becomes the responsibility of the analyst to insure that the coordinate systems used on these GRIDs are as desired. Once the coordinate system transformations are done, the matrices are arranged into external sort order (DOF arranged in ascending GRID/SPOINT ID order).

Step Four: Reducing & Re-Mapping DOFs

The next steps are the most difficult for the analyst to implement: insuring that both the number *and order* of the DOFs from both models are the same. It is crucial that any given row in both the [ϕ_i] matrices correspond to the same type of motion of the same point on the actual structure. There are two considerations for the analyst here; first that the same set of physical DOFs are represented in both [ϕ_i] matrices, and second, that those DOFs are in the same order. First a description of the manual approach for reducing and re-ordering (tolerable for smaller, simpler models) will be presented, and then the automatic approach (the only practical approach for larger, real-world models).

The first consideration when using the "manual" approach is to insure that both models have the same number of DOFs (the *order* of those DOF will be addressed next). The simplest case would occur if both models have the same number of GRIDs in each model, then no reduction would be required. However, that circumstance is not very likely to happen. The next simplest case would be models with different number of GRIDs, such as would be the case when comparing a coarse-meshed vs. a fine-meshed model. In this case, the coarse-meshed model should become the primary model. The analyst would then select a subset of available GRIDs/DOFs in the secondary model that "match" (represent the same, or nearly the same, point in space on the physical model) those available in the primary model. This reduction technique is activated in XCORR when ASETi (or OMITi) entries are included in the bulk data section for the XCORR run. These entries refer to the subset of GRIDs/DOFs of the secondary model that the analyst wished to use in comparison with the primary model. The DOFs selected are simply partitioned (not condensed) out from the G-set sized [ϕ_2] matrix. If the analyst wishes to reduce the primary model, it is recommended that the primary model be re-run through normal modes analysis with the appropriate ASET/OMIT entries, and then this new database used as input to XCORR.

Once the sets of DOFs from both models have been reduced to represent the same DOFs, the next task is to insure that the order of those DOFs is the same; i.e. to get row "n" of each [ϕ] matrix to correspond to the motion of the same DOF. It is virtually guaranteed that there will be no correlation in the external-sort order of grid IDs used in between the two models, and therefore the order of the DOFs must be modified if they are to line up. Using the manual approach, a DMI matrix named "DOFMAP" is used to tell XCORR of the correspondence between DOFs of the primary and secondary model; i.e. map the 7th row (DOF) of the primary model onto the 18th row

(DOF) of the secondary model. A DMI, DOFMAP bulk data entry would be required for each DOF that needs to be re-mapped. Note these DOFs for the secondary model are based on the order *after* any ASET/OMIT partitioning has occurred.

This manual technique quickly becomes very cumbersome for all but the simplest of models. The good news is that XCORR also provides an automatic technique for mapping GRIDs together. This technique is activated via PARAM, SET1, G (the default value for SET1 is "A"). Matching GRIDs are identified and verified with a three-layered decision criterion. XCORR will sequentially pick a grid from the primary model and then calculate the distance from that grid to every grid in the secondary model. Any secondary model grid that falls within a user-defined distance (see PARAMeter DSTDIFF, default = 0.1) is a potential matchup candidate. Where multiple GRIDs become candidates, the magnitude of the off-diagonal stiffness terms are checked against those terms in the primary stiffness matrix, and those falling within a certain percentage (see PARAMeter KDIFF, default = 0.1%) are kept. If matches still exist, the diagonal terms on the mass matrices are compared (PARAM, MDIFF, default = 0.1%) similarly. If matches still exist, then that grid is thrown out of consideration from both models and will not be included in the cross-orthogonality check. Then it loops back and works on the next primary model grid point. Based on the GRIDs with successful matches, the mode shape matrices are partitioned down and, if necessary, a Guyan reduction performed on the primary model's mass matrix. Lists of the resultant grid matchups are provided for the user.

As this approach involves multiple loops though some of the SUBDMAPs, the .f04 file can become *extremely* long. The user is strongly urged to use an ASSIGN statement in the FMS routing a formatted OUTPUT4 file associated with FORTRAN unit 99 to the /dev/null file (e.g.: ASSIGN OUTPUT4='/dev/null', UNIT=99, FORM=FORMATTED) . During the looping portion of the solution sequence, the normal .f04 file output is temporarily routed to this unit number.

The DOF reducing and re-mapping considerations are the most difficult part of the pre-processing of the mode shape matrices. The automatic grid mapping feature is the only practical method when using real-world sized models, and obviously requires both models be MSC/NASTRAN analyses. The manual DMI input approach would only be acceptable for small models, or when using a secondary model that comes from an external source, such as test results.

Step Five: Mode Deletion

Now that the rows of the $[\phi_i]$ matrices have been taken care of, it is time to turn our attention to the columns, the number and order of the modes themselves. The first column-wise tools XCORR provides are mode-removal tools. This tool allows the analyst to remove modes from either or both the models and not use them in the cross-correlation calculation. This might be used in the case where a fine meshed model has local modes that are not part of the other model's modes - the analyst would not want to include those modes in the cross-orthogonality check. In any case, the net result is that there must be the same number of modes in both the primary and secondary mode shape matrices. The analyst tells XCORR to remove modes through the use of DMI entries for the matrices RMVMODE1 and/or RMVMODE2 These matrices inform XCORR as to which modes (which columns of the mode shape matrices) are to be removed prior to the $[\phi_1]^T[M_1][\phi_2]$ calculation. DMI entries are only required for those modes to be removed. See the comments in the XCORR DMAP for more details and an example DMI input matrix.

Step Six: Mode Re-Ordering

The analyst may also need to, or just want to, re-arrange the order of the retained modes. With closely coupled modes it is certainly possible for the "n^{th}" mode shape from one model to show up as the "m^{th}" mode of the other model. If the order of the modes are different in the two models, the resultant modal cross-correlation matrix will have large off-diagonal coupling terms and near zero terms on the diagonal for the affected rows/columns. XCORR provides an option to re-order the secondary mode shape matrix. This feature is activated by, you guessed it, another DMI input matrix, this one named "MODESWAP". The analyst would add a MODESWAP DMI bulk data entry for each mode of the secondary model to be placed in a different column. Input is needed only for modes that are to be swapped. Note that it is the <u>secondary</u> mode shape matrix that is being re-ordered, and that the re-ordering occurs <u>after</u> any secondary model modes have been removed (see RMVMODE2 above). This feature allows the analyst to play "what-if" games with the order of the modes if so desired.

XCORR Test Input Decks

The XCORR routine is delivered with a library of simple test problems that demonstrate the various features and options within XCORR. The analyst is referred to these individual test decks for a full description of the features and options being demonstrated. Besides these test problems, XCORR has been and is being used in comparison of MSC/NASTRAN models at Analex. It has been used in comparing many real-world models of different sizes with successful results. Many of the features in XCORR were developed as a direct result of the demands of these real-life analyses.

Conclusions

The XCORR DMAP program was developed with as many modal cross-correlation features designed for the analyst as the authors could think of. It provides real-world problem solving tools for the preparation of the mode shape matrices and the post-processing of the modal cross-correlation matrix. Its features have been incorporated and enhanced as a result of its actual use in the verification of various MSC/NASTRAN models. It is the authors' collective intent that XCORR remain a user-oriented and open program, and hence user-suggested enhancements will be gratefully included and made available to the analyst community at large.