APPLICATION OF A SUBSTRUCTURE TECHNIQUE FOR STS/PAYLOAD COUPLED MODAL ANALYSIS

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ABSTRACT

A procedure is presented for substructure modal analysis in which models of the components are initially incompatible. Such incompatibility exists when model generation and component modal reduction are performed by different organizations on different computer systems. The solution technique uses MacNeal-Schwendler Corp.'s version of NASTRAN (MSC/NASTRAN) to perform the analyses. The specific application discussed is the case where the substructures are the Space Transportation System (STS) and its payload. Theoretical development is discussed, along with a brief description of results. These results include comparison of substructured and unsubstructured coupled system frequencies and mode shapes for an example problem, and frequencies obtained from an actual STS/payload coupled analysis.

NOMENCLATURE

C - compatibility matrix
I - identity matrix
K - stiffness matrix
M - mass matrix
R - reorder matrix
T - reduction transformation matrix
λ - eigenvalue
ϕ - displacement mode shape

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Subscripts

C - constrained mode
E - free, elastic degrees of freedom
I - interface degrees of freedom
N - normal mode
O - orbiter
P - payload
S - coupled system
T - compatible coupled system

Superscripts

T - matrix transpose
* - reduced matrix

INTRODUCTION

Modal analyses of launch vehicles/payload coupled systems have proven to be useful in providing structural data during the design and development of a spacecraft. However, this is often a cumbersome procedure involving the use of incompatible substructure models produced with different computer systems and programs by different organizations. This problem can be solved by using a widely accepted component mode synthesis technique, Reference 1, and the powerful capabilities of a standardized structural analysis program such as MSC/NASTRAN.

Such an analysis has been performed for the newest spacecraft delivery and retrievel system, STS, for both lift-off and landing configurations. The advantages of such a procedure are that initially incompatible substructure models may be combined and conveniently analyzed using MSC/NASTRAN. Nearly all model generation, data and matrix manipulation, and data recovery functions, may be performed with MSC/NASTRAN without each contractor formulating a separate analysis program. The results provide the spacecraft contractor with timely data for assessing launch vehicle/payload dynamic interaction and for performing transient analyses to determine member loads.

NASTRAN DATA INTERFACE

Significant data interface problems can be encountered in performing a coupled modal analysis if computer systems and/or versions of NASTRAN are not compatible. Such is often the case when more than one contractor is involved.

Details of the analysis presented herein will be for the case examined by McDonnell Douglas Astronautics Company-St. Louis (MDAC-St. Louis) using an STS model obtained from McDonnell Douglas Technical Services Company-Houston Astronautics Division (MDTSCO-HAD) through NASA/JSC. The principal differences in the preparation and form of the STS and the MDAC-St. Louis payload models are shown in Figure 1. Since the coupled analysis, when performed for payload development purposes, is done by the payload contractor, STS model data (mass, stiffness, and transformation matrices) must be converted to a form which may be directly input into MSC/NASTRAN using its binary tape reading module (INPUTT4).

These difficulties may be overcome by transmitting the data on magnetic tape in BCD form. The necessary conversion is accomplished by two FORTRAN processing programs. The STS modeling agency converts the data from its host computer form, in this case UNIVAC binary, to BCD. The data tape is then transmitted to the payload contractor who converts it from BCD to its analysis language, which for MDAC is CDC binary, for input into MSC/NASTRAN.

THEORETICAL DEVELOPMENT

Since the STS model provided the payload contractor is not in its initial state, but rather the result of a number of component modal reductions, the pre-programmed NASTRAN substructuring capabilities cannot be used. A procedure must be formulated which not only couples the STS and payload matrices but reduces them to an acceptably small analysis size. A method which has been found to yield good results was developed by Craig and Bampton[2], which is a modification of the method proposed by Hurty[1]. The method, as it relates to this application, is summarized in the following discussion.

For any substructure, the mass and stiffness matrices may be reordered, placing all degrees of freedom which are slated to be joined with other substructures in the upper-left rows and columns, by using a reorder matrix R through the transformation.

$$[M_R] = [R]^T[M][R]$$

and

$$[K_R] = [R]^T[K][R]$$

The mass and stiffness matricies may then be partitioned to form

$$[M_R] = \left[\begin{array}{c:c} M_{II} & M_{IE} \\ \hdashline M_{EI} & M_{EE} \end{array}\right]$$

and

$$[K_R] = \left[\begin{array}{c:c} K_{II} & K_{IE} \\ \hdashline K_{EI} & K_{EE} \end{array}\right].$$

For a redundant connection between substructures, there exists a set of constraint modes, ϕ_C, which are the deflections of the internal degrees of freedoms due to a unit displacement of each of the interface degrees of freedom. They can be written as:

$$[\phi_C] = - [K_{EE}]^{-1}[K_{EI}]$$

The normal of elastic modes for this system, as if the interface degrees of freedom were constrained, ϕ_N, can also be obtained, by solving for the eigenvectors of the system

$$[K_{EE} - \lambda_N^j \, M_{EE}] \, \{\phi_N^j\} = \{0\}.$$

A transformation matrix can then be formed using these two mode shapes, namely:

$$[T] = \left[\begin{array}{c|c} I & 0 \\ \hline \phi_C & \phi_N \end{array}\right]$$

Using this transformation matrix, the physical degrees of freedom of the analysis set can be reduced to a smaller set consisting of physical interface degrees of freedom and a set of generalized coordinates by the triple products

$$[M^*] = [T]^T[M_R][T]$$

and

$$[K^*] = [T]^T[K_R][T]\,.$$

This reduction procedure is performed for both substructures, STS and payload; and the results form the matrices which are to be joined for the coupled analysis.

To perform the coupled modal analysis, the reduced mass and stiffness matrices are first merged in diagonal form

$$[M_S] = \left[\begin{array}{c|c} M_0^* & \\ \hline & M_P^* \end{array}\right]$$

and

$$[K_S] = \left[\begin{array}{c|c} K_0^* & \\ \hline & K_P^* \end{array}\right].$$

The substructures are, however, still uncoupled due to the duality of interface degrees of freedom. A compatibility condition must be applied to equate the interface degrees of freedom in the orbiter to those of the payload. Assuming each model has the interface degrees of freedom in the first rows and columns, the compatibility matrix can be written as:

$$[C] = \left[\begin{array}{c|c|c} I & 0 & 0 \\ \hline 0 & I & 0 \\ \hline I & 0 & 0 \\ \hline 0 & 0 & I \end{array}\right] \begin{array}{l} \text{Orbiter Interface Degrees of Freedom} \\ \text{Other Orbiter Degrees of Freedom} \\ \text{Payload Interface Degrees of Freedom} \\ \text{Other Payload Degrees of Freedom} \end{array}$$

The total system matrices are then:

$$[M_T] = [C]^T[M_S][C]$$

and

$$[K_T] = [C]^T[K_S][C].$$

The system eigenvalues and eigenvectors are those of:

$$[K_T - \lambda_T^j M_T]\{\phi_T^j\} = \{0\}$$

To obtain the modal deflections in physical coordinates the transformation process must be reversed:

$$[\phi_S] = [C][\phi_T],$$

where ϕ_S may be partioned into orbiter and payload parts becoming:

$$[\phi_S] = \left[\begin{array}{c} \overset{*}{\phi}_{TO} \\ \hline \overset{*}{\phi}_{TP} \end{array}\right].$$

Separating the payload portion of the total system mode shape and transforming, the modal deflections in physical coordinates can be written as:

$$[\phi_{TP}] = [R_p][T_p][\overset{*}{\phi}_{TP}].$$

The same transformations are performed on the orbiter portion of ϕ_T, to obtain its portion of the total system mode shape.

The preceeding procedure has been implemented by the use of NASTRAN DMAP's and Rigid Formats.

NASTRAN IMPLEMENTATION

For debugging and data handling purposes, the above procedure is performed in three separate steps as shown in Figure 2. The STS model obtained, in this case, from MDTSCO-HAD is in the reduced form and may be directly coupled to the corresponding payload matrices. A transformation matrix is also provided to obtain STS mode shapes in physical coordinates.

For the payload, the mass and stiffness matrices are generated by a Rigid Format analysis and output to tape. Tables which define grid point displacement and element property parameters are also saved to later obtain modal displacements and forces in a useful form. Often Guyan reduction is also necessary. If so, the Guyan reduction transformation matrix must also be saved.

The data generated by the first step is input, transformation matrices assembled, and reduction performed to complete the second step.

Finally, for the coupled analysis, all previously generated data is input, STS and payload, and total system matrices are formed. Total system modes and frequencies are then computed and the mode shapes for both STS and payload are blownback to physical coordinates. A modal force matrix for the payload may also be calculated for subsequent transient analyses. Further insight into implementation may be provided by examining a sample case.

EXAMPLES AND RESULTS

In order to show correlation between substructured and unsubstructured analyses and establish data handling procedures, the analysis was first performed using "stick" models, shown in Figure 3, representing two generic substructures. The DMAP's for steps 2 and 3 of the substructured analysis are shown in Figures 4 and 5, respectively.

Frequencies and mode shapes for a coupled model using the substructuring technique were computed. The analysis was then repeated using an unsubstructured or total system model. Frequencies obtained by the two techniques have good correlation, as shown by the comparison in Figure 6. The first mode shape obtained by the two procedures is identical to greater than four significant figures. A tabular listing of the payload portion of Mode 2 is given in Figure 7.

Sample results from an actual STS/payload coupled modal analysis are shown in Figure 8. The case analyzed is a landing configuration (orbiter plus payload). The first three columns list the frequencies for STS and payload structures analyzed separately and for the coupled model, respectively. The final column denotes the type of coupled mode, i.e. "payload" or "STS", indicating significant elastic displacement in only that substructure, and "coupled" referring to responses of similar magnitude in both substructures. On examination of the results, it is apparent that a significant degree of modal coupling is present. For example, the first two coupled modes are combinations of the first STS and payload modes.

SUMMARY

Due to the potential of modal coupling between the STS launch vehicle and the payloads which it carries, a coupled modal analysis becomes a useful tool. Its results provide dynamic response data for payload design and development by providing a means of assessing dynamic interaction and supplying modal data for analysis of launch and landing transient events. Using the NASTRAN procedure outlined above, the analysis can be performed with relative ease and in a cost-effective manner, with a high degree of confidence in the results.

ACKNOWLEDGEMENT

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REFERENCES

1. Hurty, W. C., "Dynamic Analysis of Structural Systems by Component Mode Synthesis," Report 32-530, 1964, Jet Propulsion Laboratory, Pasadena, CA.

2. Craig, R. R. and Bampton, M. C. C., "Coupling of Substructures for Dynamic Analysis," AIAA Journal, Volume 6, No. 7, July 1968.

SUBSTRUCTURE	STS	PAYLOAD
ORGANIZATION	MDTSCO-HAD	MDAC-ST. LOUIS
COMPUTER SYSTEM	UNIVAC 1108	CDC CYBER 175
CODE	BCD-72 BITS/WORD	CDC-60 BITS/WORD
PRECISION	DOUBLE	SINGLE
TAPE TYPE	7 TRACK, 800 BPI	9 TRACK, 1600 BPI
NASTRAN I/O FUNCTIONS	NASA/JSC COSMIC	MSC
	INPUTT2/OUTPUT2	INPUTT4/OUTPUT4

FIGURE 1 NASTRAN DATA INTERFACE

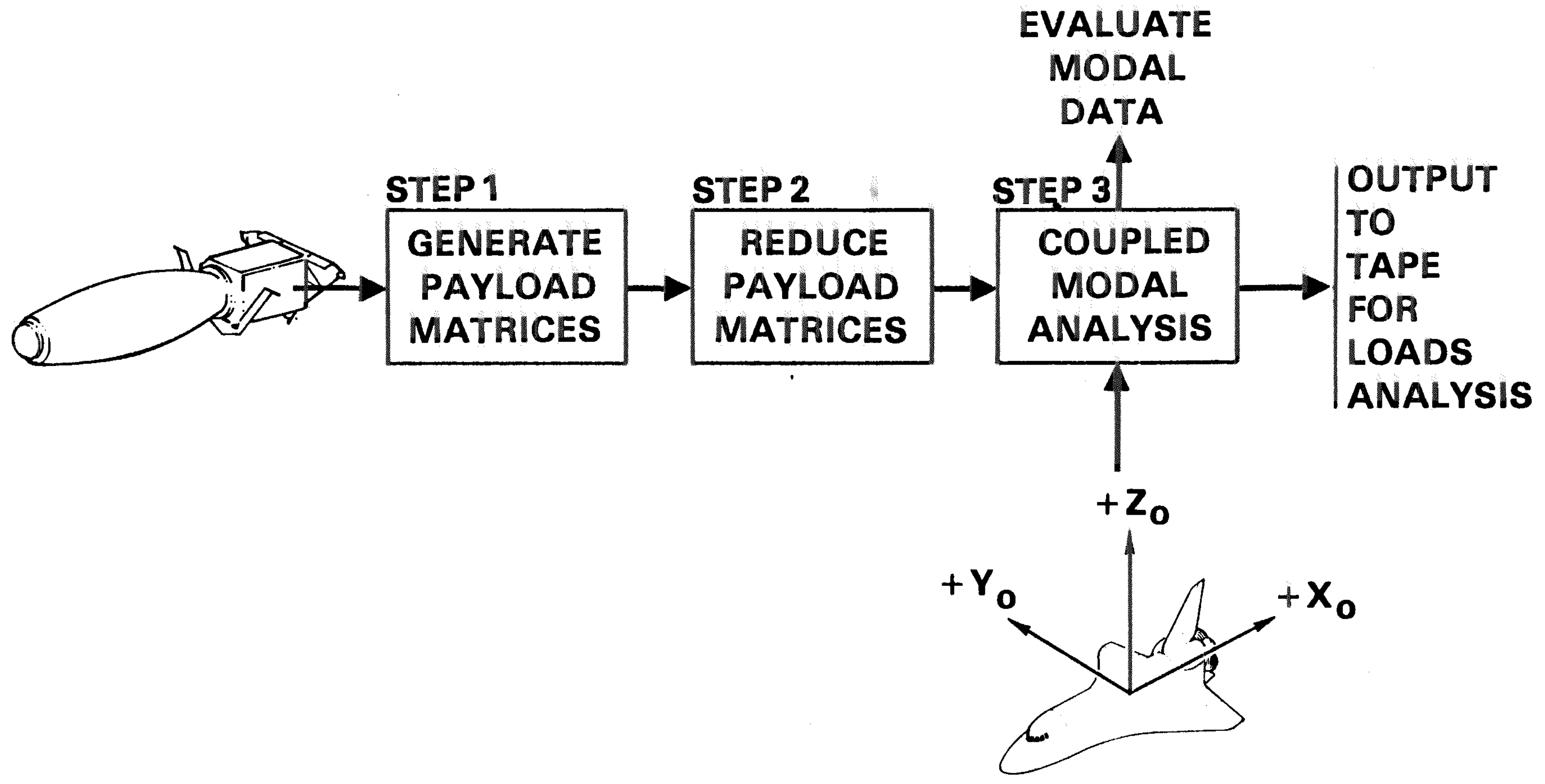
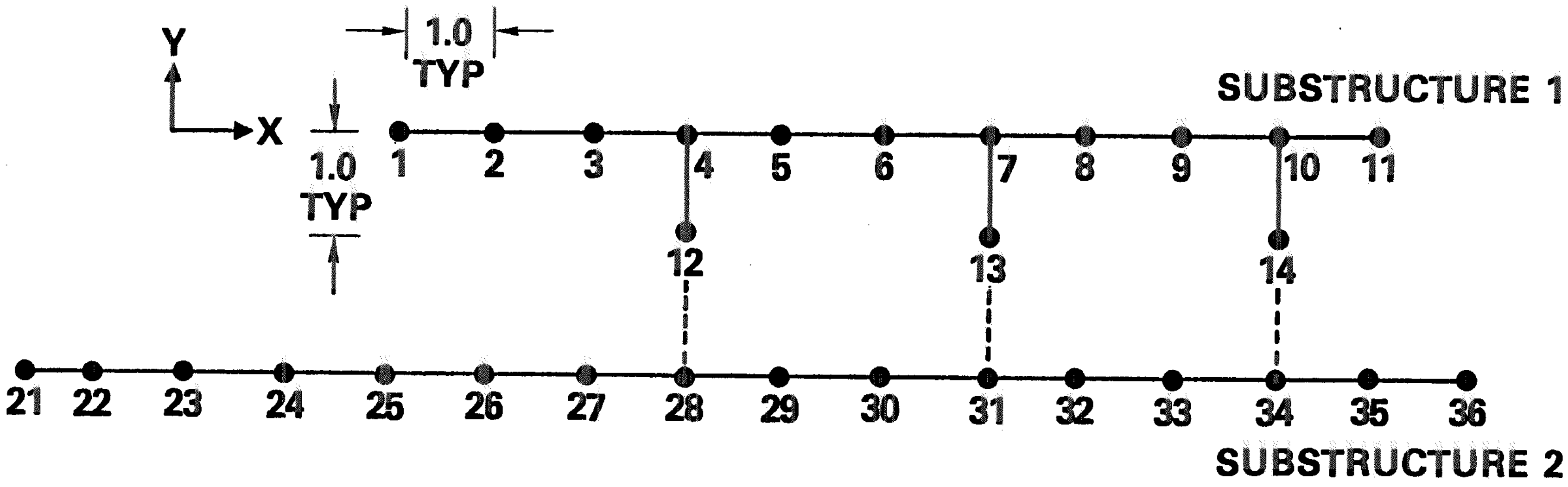


FIGURE 2 STS/PAYLOAD COUPLED MODAL ANALYSIS STEPS



PLANAR MODEL — TWO TRANSLATIONS AND ONE ROTATION

FIGURE 3 COUPLED MODAL ANALYSIS EXAMPLE PROBLEM MODEL

```
BEGIN $
PARAM //SYST/V,N,DUM/-2152/134479872 $
PARAM //SYST/DUM/-755/0 $
INPUTT4 /MPLD,KPLD,,,/2/11/-1 $
INPUTT2 /EQEXIN,SIL,BGPDT,USET,MPT1/0/11 $
INPUTT2 /EST,,,,/0/11 $
$
$  REORDER M AND K
$
SMPYAD ROM,MPLD,ROM,,,/MS/3/1/0/1/1 $
SMPYAD ROM,KPLD,ROM,,,/KS/3/1/0/1/1 $
$
$  COMPUTE STATIC MODES
$
PARTN MS,C2,/,,,MEEP/-1 $
PARTN KS,C2,/,KEIP,,KEEP/-1 $
SOLVE KEEP,KEIP/VG/1/-1/1/1 $
$
$  COMPUTE CONSTRAINED ELASTIC MODES
$
MATGEN ,/D2/1/5 $
MERGE D2,VG,,,,C2/VGU/1 $
READ KEEP,MEEP,,,DYNAMICS,,CASECC/LAMP,PHIP,PO,PEI/C,N,MODES/V,N,NEIGV $
LAMX ,,LAMP/LAMPM/-1 $
MERGE ,PHIP,,,,C2/PHIY/1 $
$
$  FORM REDUCED M AND K
$
MERGE VGU,,PHIY,,C1,/TP/1 $
SMPYAD TP,MS,TP,,,/MP/3/1/0/1/1 $
SMPYAD TP,KS,TP,,,/KP/3/1/0/1/1 $
NORM PHIP/PHIPN/ $
MPYAD ROM,PHIY,/PHIRO/ $
UMERGE USET,PHIRO,/PHIGG/C,Y,MAJOR=G/C,Y,SUB0=F/C,Y,SUB1=SB $
NORM PHIGG/PHIG/ $
SDR2 CASECC,,,,EQEXIN,SIL,,,BGPDT,LAMP,,PHIG,,/,,OPHIG,,OEF1,/
     C,N,REIG $
$
$  PRINT RESULTS
$
OFP LAMP,PEI,,,,// $
MATPRN PHIP,PHIPN,TP,,// $
MATPRN MP,KP,,,// $
OFP OPHIG,OEF1,,,,// $
$
$  OUTPUT RESULTS ON TAPE OR DISK FILE
$
OUTPUT4 ROM,TP,MP,KP,//-1/12 $
SEEMAT VGU,,,,// $
END $
```

FIGURE 4 NASTRAN DMAP FOR PAYLOAD MATRIX REDUCTION

```
BEGIN $
PARAM //SYST/V,N,DUM/-2152/134479872 $
PARAM //SYST/DUM/-755/0 $
INPUTT4 /MORB,KORB,BO,MPLD,KPLD/5/11/-1 $
INPUTT4 /GM,GO,S,TP,MP/5/11/0 $
INPUTT4 /KP,,,,/1/11/0 $
INPUTT2 /EQEXIN,SIL,BGPDT,USET,MPT1/0/11 $
INPUTT2 /EST,,,,/0/11 $
$
$  ASSEMBLE MASS & STIFFNESS MATRICIES
$
MERGE MORB,,,MP,C1,/M/ $
MERGE KORB,,,KP,C1,/K/ $
$
$  APPLY COMPATIBILITY CONDITION
$
SMPYAD CR,M,CR,,,/MRSYS/3/1/0/1/1 $
SMPYAD CR,K,CR,,,/KRSYS/3/1/0/1/1 $
$
$  COMPUTE ELASTIC MODES
$
READ KRSYS,MRSYS,,,DYNAMICS,,CASECC/LAMA,PHI,PO,PEI/C,N,MODES/
     V,N,NEIGV $
$
$  COMPUTE TRANSFORMATION MATRICIES AND
$  BLOWBACK TOTAL SYSTEM MODES
$
LAMX ,LAMA/LAMS/-1 $
MPYAD CR,PHI,/CRPHI/ $
PARTN CRPHI,,C1/PHI1,PHI2,,/1 $
MPYAD S,TP,/STP/ $
MPYAD STP,PHI2,/PHIF/ $
UMERGE USET,PHIF,/PHIGG/C,Y,MAJOR=G/C,Y,SUB0=F/C,Y,SUB1=SB $
MPYAD BO,PHI1,/PHIORB/ $
MERGE PHIORB,PHIGG,,,,C2/PHICS/1 $
NORM PHICS/PHICSN/ $
PARTN PHICSN,,C2/PHIOS,PHIPS,,/1 $
SDR2 CASECC,,MPT1,,EQEXIN,SIL,,,BGPDT,LAMA,,PHIPS,EST,/,,OPHIG,,OEF1,/
     C,N,REIG $
$
$  OUTPUT RESULTS
$
OFP LAMA,PEI,,,,// $
MATPRN PHI,PHIOS,PHICS,,// $
OFP OPHIG,OEF1,,,,// $
OUTPUT4 LAMS,PHICS,,,//-1/12 $
OUTPUT2 OEF1,,,,//0/12 $
END $
```

FIGURE 5 NASTRAN DMAP
FOR COUPLED MODAL ANALYSIS

MODE	FREQUENCY — Hz	
	SUBSTRUCTURED MODEL	UNSUBSTRUCTURED MODEL
1	36.03	36.03
2	85.77	85.77
3	147.34	147.34
4	204.72	204.70
5	266.56	266.49
6	337.76	337.56
7	457.35	457.19
8	543.31	543.43
9	643.91	643.85
10	715.13	714.77

FIGURE 6 FREQUENCY COMPARISON FOR EXAMPLE CASE

JOINT	Y MODAL DISPLACEMENT (ϕ_{MAX} = 1.0)	
	SUBSTRUCTURED MODEL	UNSUBSTRUCTURED MODEL
1	−0.9475	−0.9462
2	−0.1782	−0.1782
3	0.3802	0.3795
4	0.5051	0.5045
5	0.2035	0.2034
6	−0.1663	−0.1659
7	−0.1869	−0.1865
8	−0.1547	−0.1544
9	−0.2661	−0.2657
10	−0.0316	−0.0316
11	0.5557	0.5545
12	0.5052	0.5045
13	−0.1868	−0.1865
14	−0.0317	−0.0317

FIGURE 7 COMPARISON OF MODAL DISPLACEMENTS FOR EXAMPLE CASE - MODE 2

MODAL FREQUENCIES (Hz)			COMMENTS
STS	PAYLOAD	COUPLED	
		3.90	COUPLED MODE
3.99			
	4.12		
		4.12	COUPLED MODE
		5.30	COUPLED MODE
5.53			
	6.82	6.71	PAYLOAD MODE
		6.98	COUPLED MODE
7.07			
		7.16	COUPLED MODE
	7.19		
7.42		7.45	STS MODE
7.88		7.90	STS MODE
	7.98	7.94	PAYLOAD MODE
8.84		8.86	STS MODE

FIGURE 8 STS/PAYLOAD COUPLED MODAL ANALYSIS FREQUENCIES —LANDING CONFIGURATION—