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MODAL REDUCTION STRATEGIES FOR INTERCONNECTED FLEXIBLE BODIES SIMULATION

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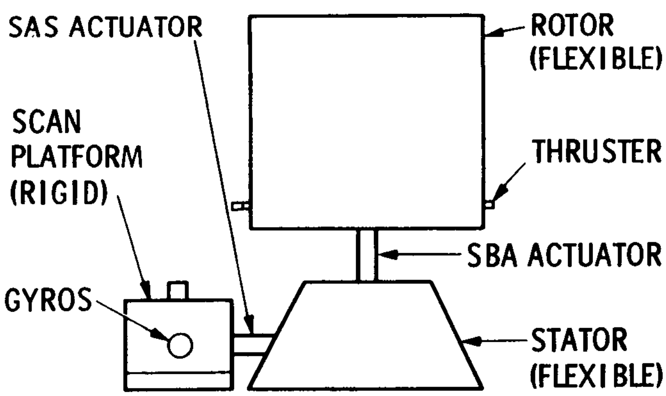
INTRODUCTION

MULTI-BODY DYNAMICS PROGRAMS REQUIRE CHARACTERIZATION OF EACH BODY

- RIGID BODY: GEOMETRY AND MASS PROPERTIES
- FLEXIBLE BDOY
  - EXACT TYPE OF INPUT DEPENDS ON PROGRAM
  - ALL INVOLVE MODAL CHARACTERISTICS IN SOME FORM
  - ALWAYS NEED FOR MODAL TRUNCATION
  - SYSTEMATIZE TRUNCATION PROCEDURE

GALILEO SPACECRAFT

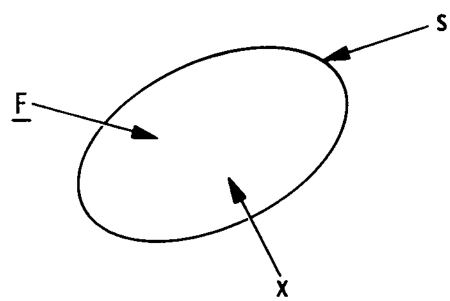
- ACTUATORS: SBA, SAS, THRUSTERS
- SENSORS: GYROS, CLOCK AND CONE ENCODERS, SUN SENSOR, STAR SCANNER
- CLOCK (SBA) CONTROL LOOP IS ACTIVE DURING ALL ATTITUDE CONTROL MANEUVERS
  - CLOCK CONTROLLER BANDWITCH ≅ 0.5 Hz
  - GYRO ROLLOFF FREQUENCY ≅ 15 Hz
- NEED "ADEQUATE" MODEL OF PLANT FOR DESIGN AND SIMULATION



TRUNCATION CRITERIA

- CONTROL SYSTEM SPECIFICATIONS CAN SET TRUNCATION CRITERIA AT SYSTEM LEVEL ONLY
  - SYSTEM MODE WITH FREQUENCY ABOVE 15Hz CAN BE DROPPED
  - ELIMINATE MODES THAT DO NOT INTERACT "STRONGLY" WITH THE CONTROL SYSTEM

SYSTEM LEVEL TRUNCATION



METHOD

$$M\ddot{x} + Kx = F \quad (1)$$

$$x = \phi z \quad (2)$$

$$X(s) = \underbrace{\phi (s^2 I + \omega^2)^{-1} \phi^T}_{D} F(s) \quad (3)$$

FOR RESPONSE AT i LOCATION DUE TO STEP INPUT AT j LOCATION,

$$X_i(s) = DijFj(s) = \sum_{k=1}^{m} \left\{ \phi_{ik} \phi_{jk} A / \left[s (s^2 + \omega_k^2) \right] \right\} \quad (4)$$

SYSTEM LEVEL TRUNCATION (CONT'D)

CONTRIBUTION OF kth MODE TO RESPONSE:

$$X_i^k(s) = \phi_{ik} \; \phi_{jk} \, A / \left[s (s^2 + \omega_k^2) \right] \tag{5}$$

OR

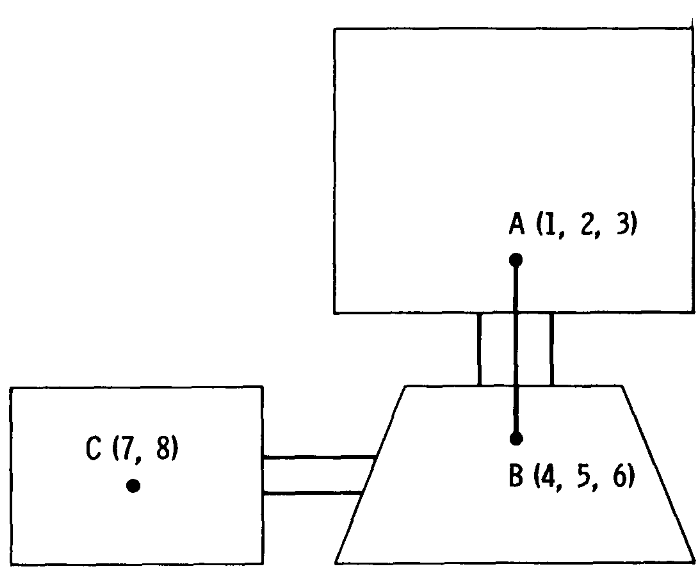
$$X \, x_i^k \, (t) = (\phi_{ij} \; \phi_{jk} \, A / \omega_k^2) \; \left[1 - \cos (\omega_k t) \right] \tag{6}$$

SINUSOIDAL RESPONSE WITH PEAK-TO-PEAK AMPLITUDE TO

$$X_i^k = 2 \; \phi_{ik} \; \phi_{jk} \, A / \omega_k^2 \tag{7}$$

A MEASURE OF IMPORTANCE OF MODE K

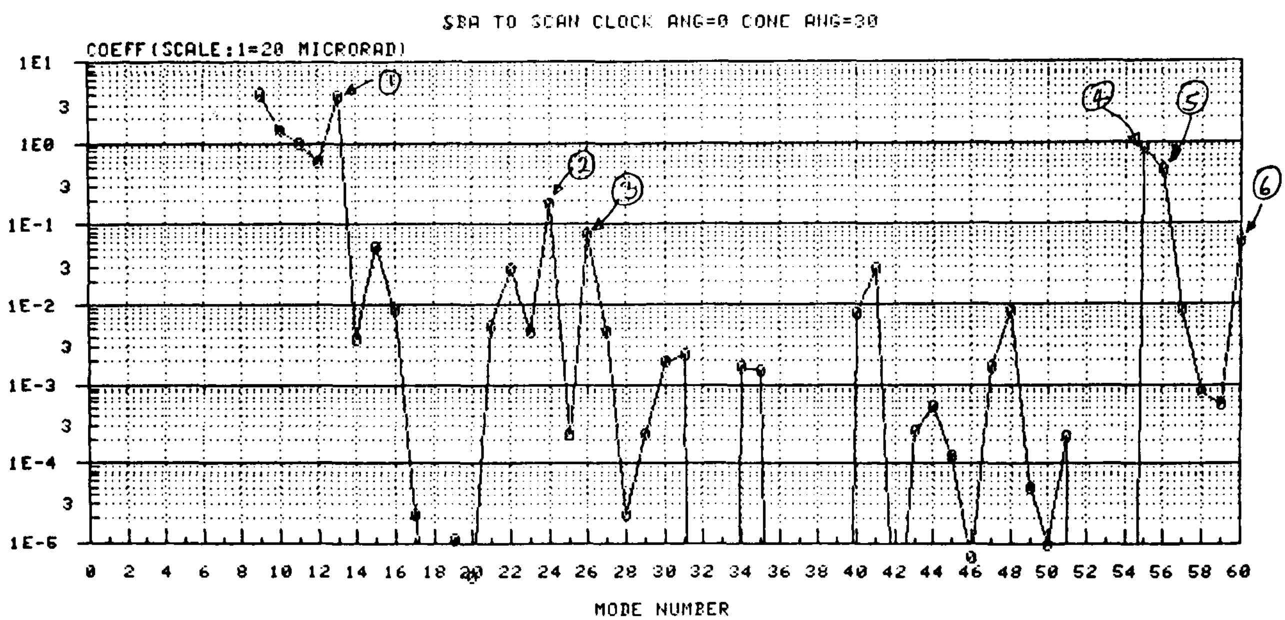
APPLICATION TO GALILEO



APPLICATION TO GALILEO (CONT'D)

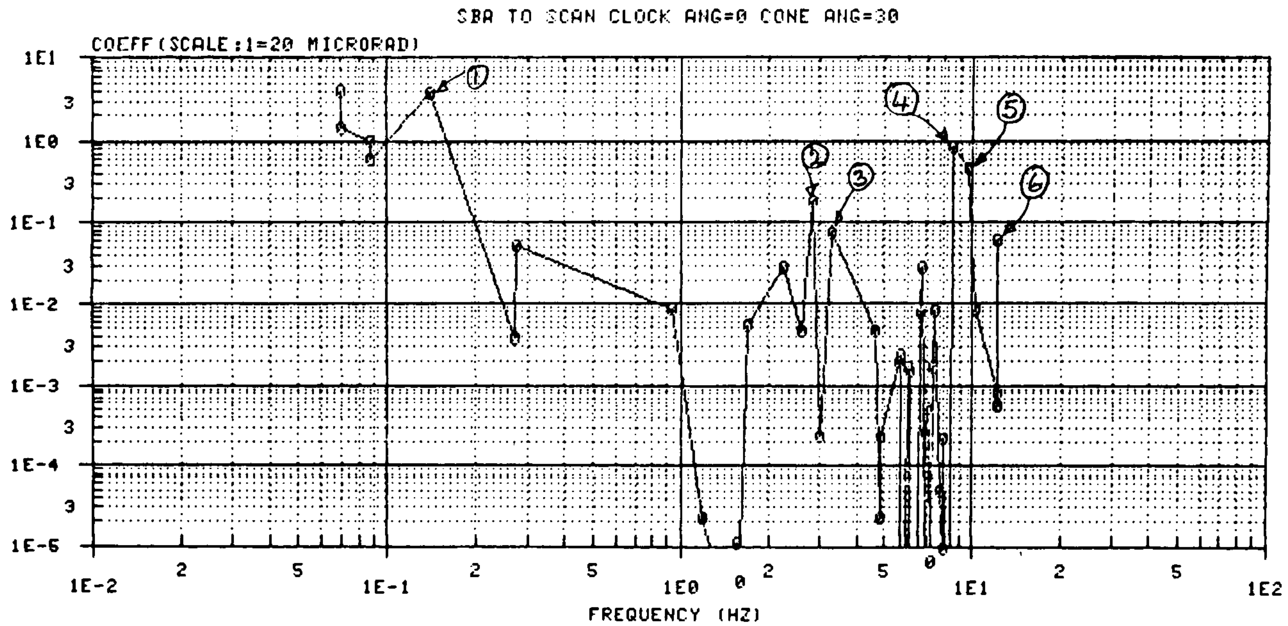
- AVAILABLE DATA
  - EIGENVALUES, EIGENVECTORS FOR UP TO 60 MODES
- PLOT MODAL INFLUENCE COEFFICIENTS
- DISCARD MODES WITH "LOW" COEFFICIENTS
- USE BODE PLOT TO CHECK RESULTS

MODAL INFLUENCE COEFFICIENTS

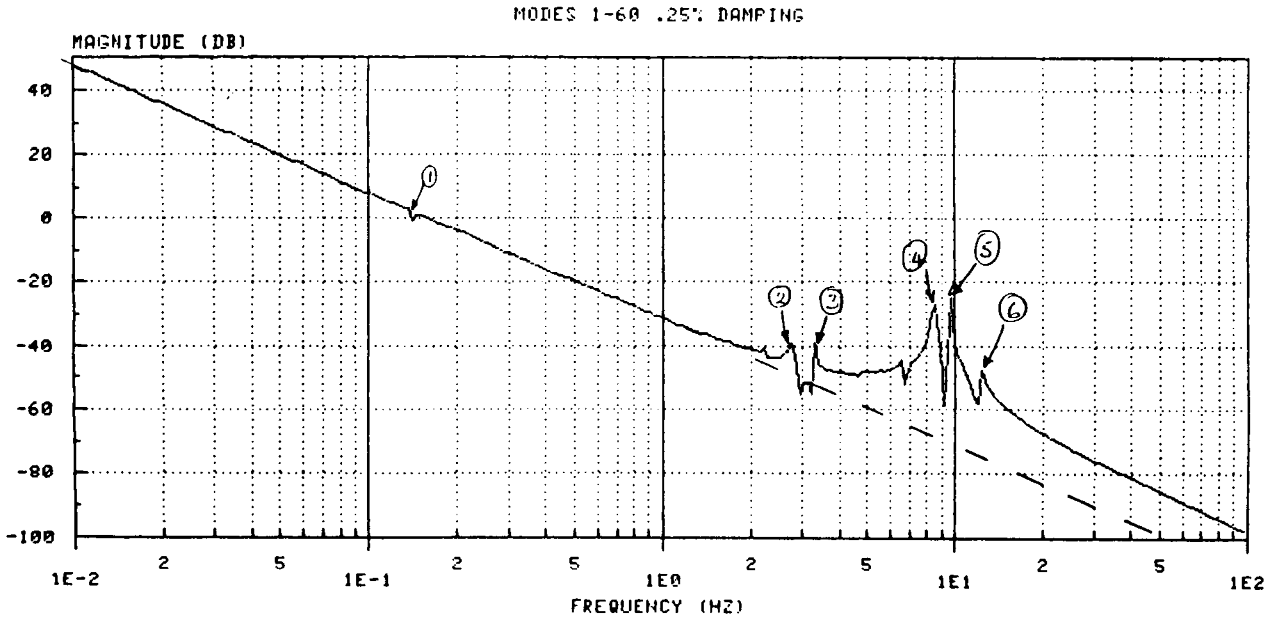


MODAL INFLUENCE COEFFICIENTS

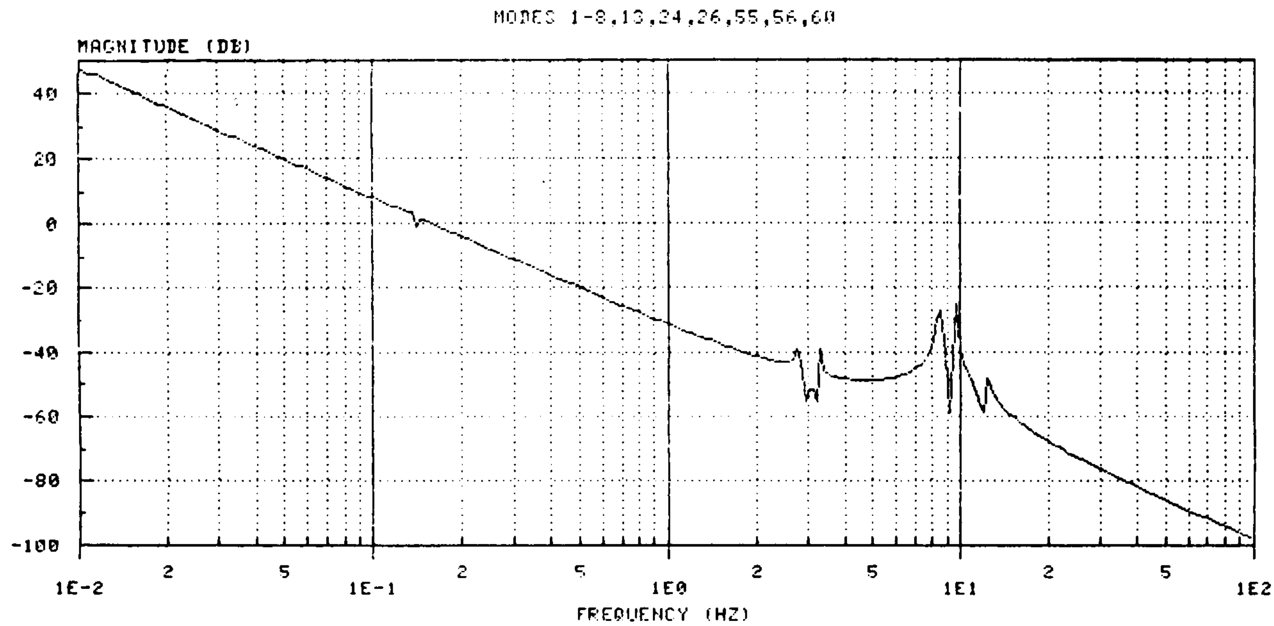
ORIGINAL PAGE IS OF POOR QUALITY



BODE PLOT OF PLANT ALPHA = 0 BETA = 30



BODE PLOT OF PLANT CLOCK = 0 CONE = 30



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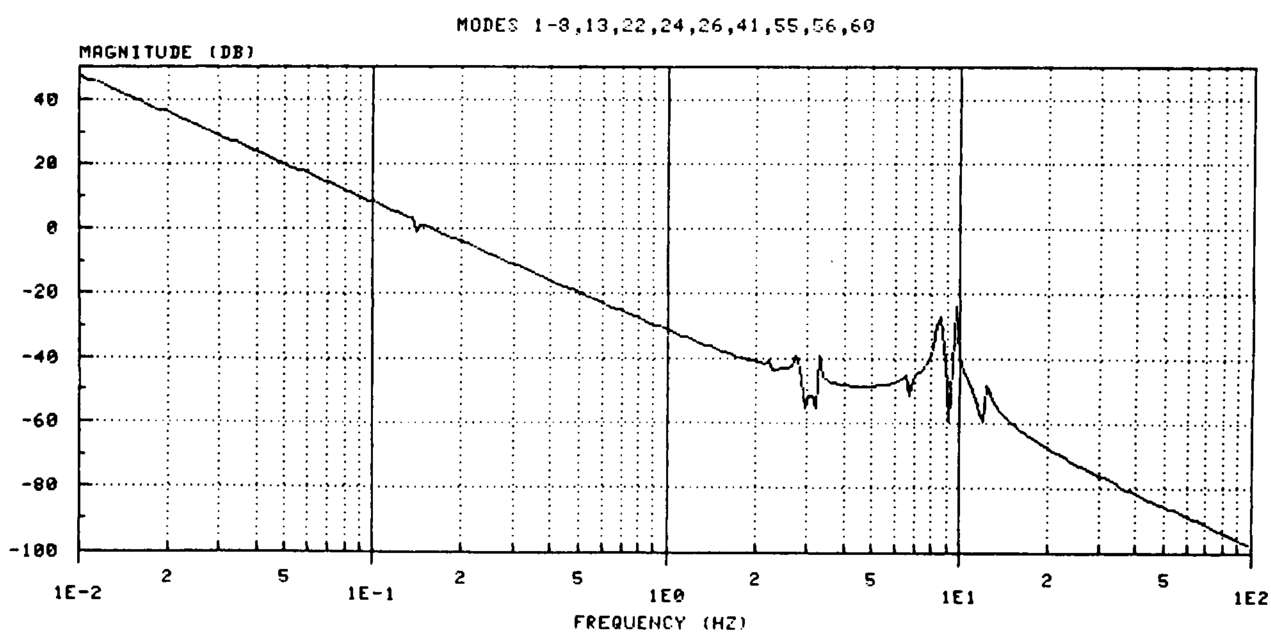
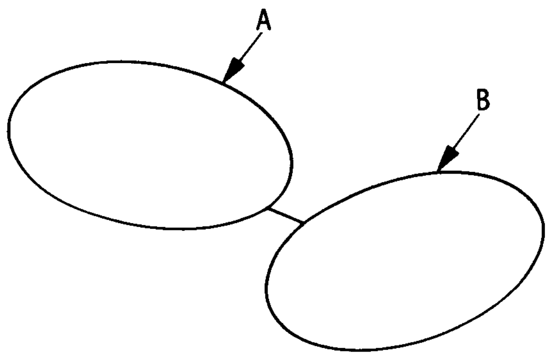


TRUNCATION AT COMPONENT LEVEL

- AVAILABLE
  - COMPONENT "FREE-FREE" MODES
  - SYSTEM MODES TO BE RETAINED
- PROBLEM
  - DETERMINATION OF "IMPORTANT" COMPONENT FREE-FREE MODES FROM KNOWLEDGE OF SYSTEM MODES
- SOLUTION
  - RETAIN THOSE COMPONENT MODES THAT "CONTRIBUTE SUBSTANTIALLY" TO IMPORTANT SYSTEM MODES

COMPONENT LEVEL TRUNCATION (CONT'D)

$$\left.\begin{aligned} M_A \ddot{x}_A + K_A x_A &= F_A \\ x_A &= \phi_A q_A \\ I\ddot{q}_A + \omega^2 q_A &= \phi_A^T F_A \end{aligned}\right\} \begin{array}{l} \text{BODY A} \\ \text{D.O.F.} = n_A \end{array} \qquad (8)$$



$$\left.\begin{aligned} M_B \ddot{x}_B + K_B x_B &= F_B \\ x_B &= \phi_B q_B \\ I\ddot{q}_B + \omega_B q_B^2 &= \phi_B^T F_B \end{aligned}\right\} \begin{array}{l} \text{BODY B} \\ \text{D.O.F.} = n_B \end{array} \qquad (9)$$

$$\left.\begin{aligned} M\ddot{x} + Kx &= F \\ x &= \phi q \\ I\ddot{q} + \omega^2 q &= \phi^T F \end{aligned}\right\} \begin{array}{l} \text{COMBINED} \\ \text{SYSTEM} \\ \text{D.O.F.} = n \leqslant (n_A + n_B) \end{array} \qquad (10)$$

COMPONENT LEVEL TRUNCATION (CONT'D)

- SYSTEM AUGMENTED ϕ MATRIX = $\bar{\phi}$
  - SYSTEM MATRIX WITH SOME ROWS REPEATED

$$\left\{\begin{array}{c} x_1 \\ x_2 \\ \vdots \\ x_{n_A} \\ \hline x_{n_A} \\ \vdots \\ x_{n_A+n_B} \end{array}\right\} = \left[\begin{array}{cccc} \phi_{11} & \phi_{12} & \cdots & \phi_{1m} \\ \phi_{21} & \phi_{22} & \cdots & \phi_{2m} \\ & & & \\ \phi_{n_A 1} & \phi_{n_A 2} & \cdots & \phi_{n_A m} \\ \hline \phi_{n_{A+1},1} & & \cdots & \phi_{n_{A+1},m} \\ & & & \\ \phi_{n'_1} & \phi_{n'_2} & \cdots & \phi_{n'm} \end{array}\right] \left\{\begin{array}{c} q_1 \\ q_2 \\ \\ q_{n_A} \\ \hline q_{n_{A+1}} \\ \\ q_{n'} \end{array}\right\} \begin{array}{l} \leftarrow \bar{\phi}_A \\ \\ \\ \leftarrow \bar{\phi}_B \end{array} \qquad (11)$$

- PARTITION $\bar{\phi}$ INTO $\bar{\phi}_A$ AND $\bar{\phi}_B$

COMPONENT LEVEL TRUNCATION (CONT'D)

- DELETE COLUMNS OF $\bar{\phi}$ THAT CORRESPOND TO SYSTEM MODES THAT WERE DROPPED
- REDUCED ϕ MATRICES: $\hat{\phi}_A$ AND $\hat{\phi}_B$
- USE $\hat{\phi}_A$ AND $\hat{\phi}_B$ AS TRANSFORMATION MATRICES FOR BODIES A AND B RESPECTIVELY
  - $\hat{\phi}_A^T M_A \hat{\phi}_A \ddot{\hat{q}}_A + \hat{\phi}_A^T K_A \hat{\phi} \hat{q}_A = \hat{\phi}_A^T F_A$ (12)

OR

  - $\hat{M}_A \ddot{\hat{q}}_A + \hat{K}_A \hat{q}_A = \hat{\phi}_A^T F_A$ (13)
  - $\hat{M}_B \ddot{\hat{q}}_B + \hat{K}_B \hat{q}_B = \hat{\phi}_B^T F_B$ (14)

COMPONENT LEVEL TRUNCATION (CONT'D)

- $\hat{M}_A, \hat{K}_A, \hat{M}_B, \hat{K}_B$ NOT NECESSARILY DIAGONAL
- DIAGONALIZE VIA ANOTHER MODAL ANALYSIS
  - $\hat{q}_A = \psi_A \bar{q}_A$ (15)
  - $\hat{q}_B = \psi_B \hat{q}_B$ (16)

$$I\ddot{\bar{q}}_A + \bar{\omega}_A^2 \bar{q}_A = \psi_A^T \hat{\phi}_A^T F \quad (17)$$

$$I\ddot{\bar{q}}_B + \bar{\omega}_B^2 \bar{q}_B = \psi_B^T \hat{\phi}_B^T F \quad (18)$$

COMPONENT LEVEL TRUNCATION (CONT'D)

- $\bar{\omega}_A$, $\bar{\omega}_B$ ARE DIAGONAL; THEY ARE ALSO SUB-MATRICES OF ω_A, ω_B RESPECTIVELY, AND CONTAIN FREQUENCIES OF COMPONENT MODES TO BE RETAINED
- SIMILARLY $\Phi_A = \hat{\phi}_A \Psi_A$ AND $\Phi_B = \hat{\phi}_B \Psi_B$ ARE SUBMATRICES OF ϕ_A AND ϕ_B, AND CONTAIN THE EIGENVECTORS OF COMPONENT MODES TO BE RETAINED

SUMMARY AND CONCLUSION

- DETERMINE SYSTEM MODES TO BE RETAINED USING
  - AVAILABLE CRITERIA
  - MODAL INFLUENCE COEFFICIENTS
  - BODE
- DESCEND TO COMPONENT LEVEL VIA A TWO-PHASE DIAGONALIZATION PROCESS STARTING WITH SUBMATRICES OF TRUNCATED AUGMENTED SYSTEM MODAL MATRIX

FUTURE WORK

- STREAMLINE SIMULATION CODES – ESPECIALLY DYNAMICS FORMULATION METHOD
- DEVELOP VERY EFFICIENT AND EASILY IMPLEMENTABLE MODEL REDUCTION STRATEGY