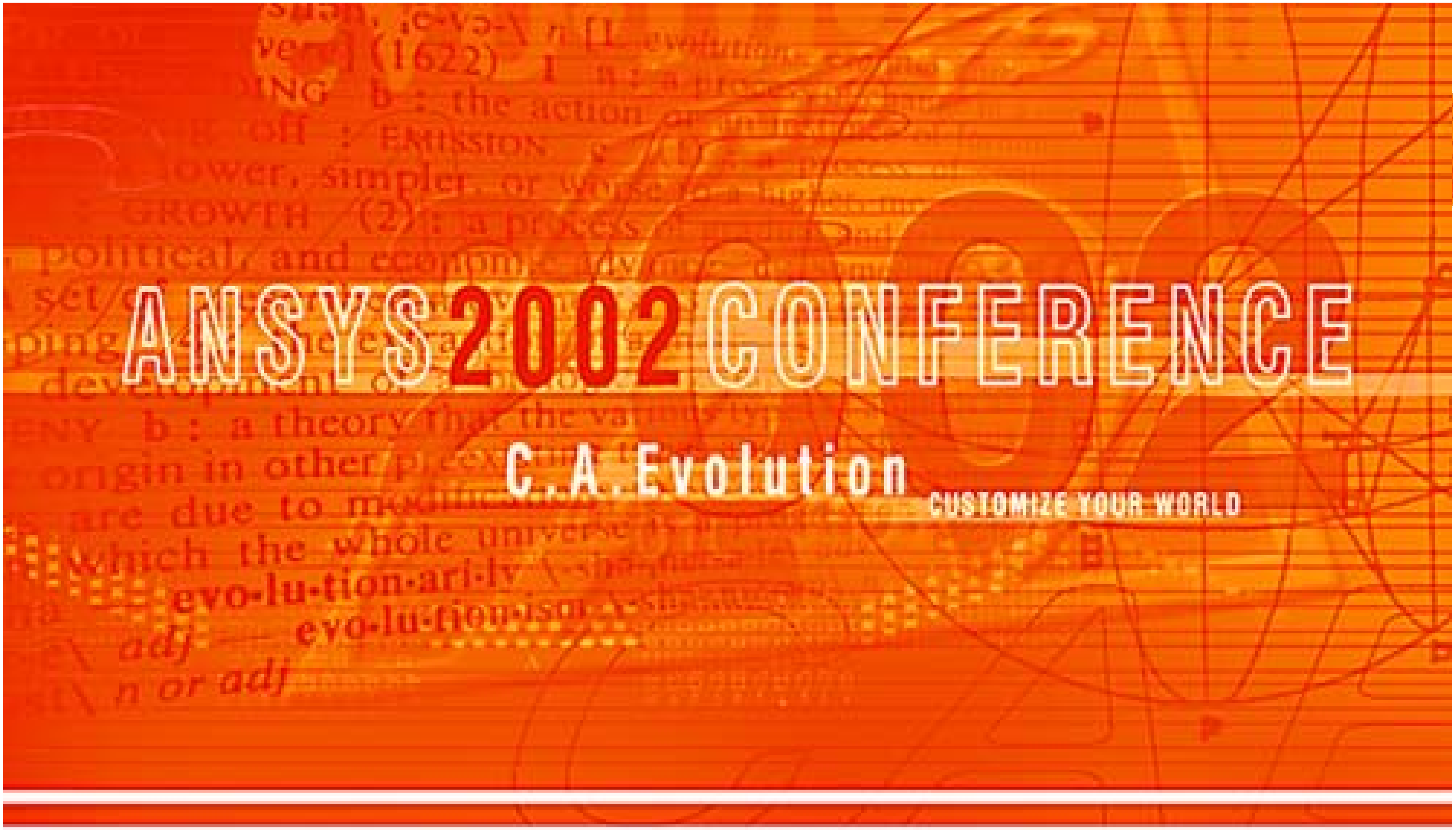
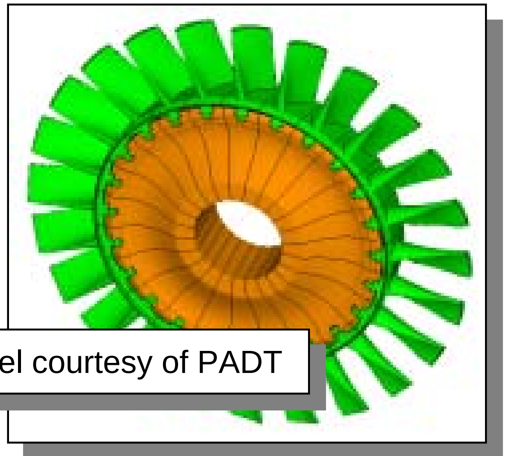


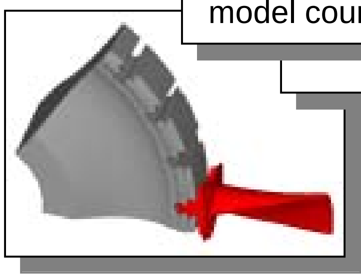
Cyclic Symmetry Analysis

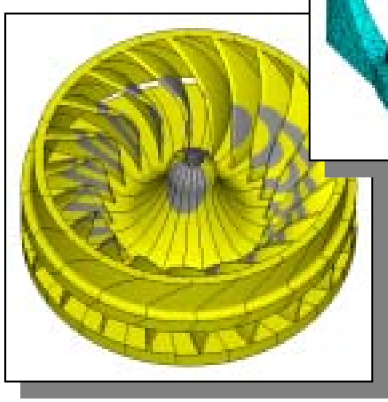
Mechanics & Simulation Support Development Group

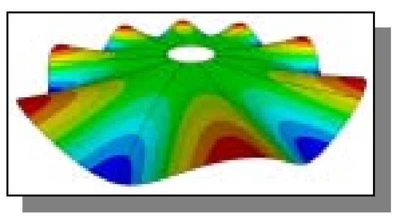
Overview



model courtesy of PADT

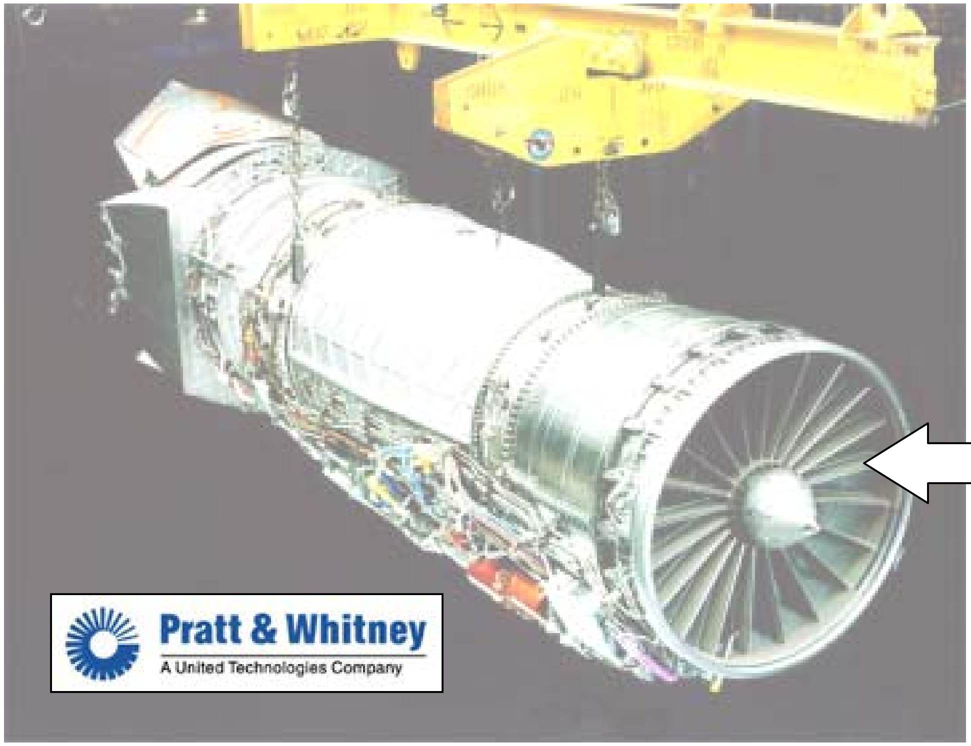






- Why Cyclic Symmetry?
- Theory
- Implementation
- Commands
- Supported Analysis Types
- Analysis Guide
- Example Models
- Future Efforts
- F.A.Q.'s

Why Cyclic Symmetry?



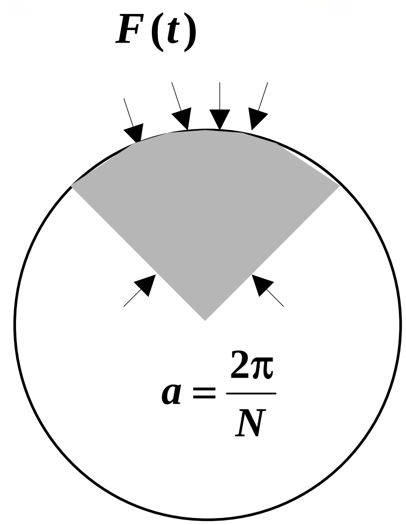
F119 engine image courtesy of Pratt & Whitney http://www.pw.utc.com/

- Reduced model size
- Reduced solution time
- Widely used in rotating machinery industry:
  - Blades
  - Vanes
  - Cases
- Applications:
  - Turbines
    - Gas
    - Steam
    - Hydro-Electric
  - Pumps
  - Fans

Theory

Full Structure Dynamic Equation:

$$\boldsymbol{M}\ \ddot{\boldsymbol{x}} + \boldsymbol{C}\ \dot{\boldsymbol{x}} + \boldsymbol{K}\ \boldsymbol{x} = \boldsymbol{F}$$



Finite Fourier Series Expansion in Complex Exponential Form:

$$\boxed{F_j(t) = \sum_{p=0}^{M} f_p(t) e^{-i(j-1)pa}}$$

$$\boxed{U_j(t) = \sum_{p=0}^{M} u_p(t) e^{-i(j-1)pa}}$$

$$\boxed{i = \sqrt{-1}}$$

$$\boxed{j = 1, \cdots, N}$$

$$\boxed{p = 0, \cdots, M}$$

N : Number of substructures

a : Angle of substructures

(Substructure => Sector)

f_p : Coefficients corresponding to the *j-th* substructures

Theory (continued)

Transformation of the displacements and forces into finite Fourier series:

$U = T\,u_p$ $F = T\,f_p$

$$\boldsymbol{T = I}\;\; e^{-i(j-1)pa}$$

$\boldsymbol{j = 1, \cdots, N}$

=>

$$T = \begin{bmatrix} I \\ I\;e^{-ipa} \\ \vdots \\ I\;e^{-i(N-1)pa} \end{bmatrix}$$

Pre-multiplying the dynamic equation by the conjugate transpose of ***T* =>** $\boldsymbol{T^{*T}}$

$$\boldsymbol{T^{*T} MT\,\ddot{u}_p + T^{*T} CT\,\dot{u}_p + T^{*T} KT\,u_p = T^{*T} T\,f_p}$$

p is the nodal-diameter

$p = 0, \cdots, M$

M = N/2 for even N

M = (N - 1)/2 for odd N

Theory (continued)

The cyclic symmetry transformation relating the displacement {U} and Fourier components {u} leads to a set (p = 0, … , M) of uncoupled cyclic substructure problems.

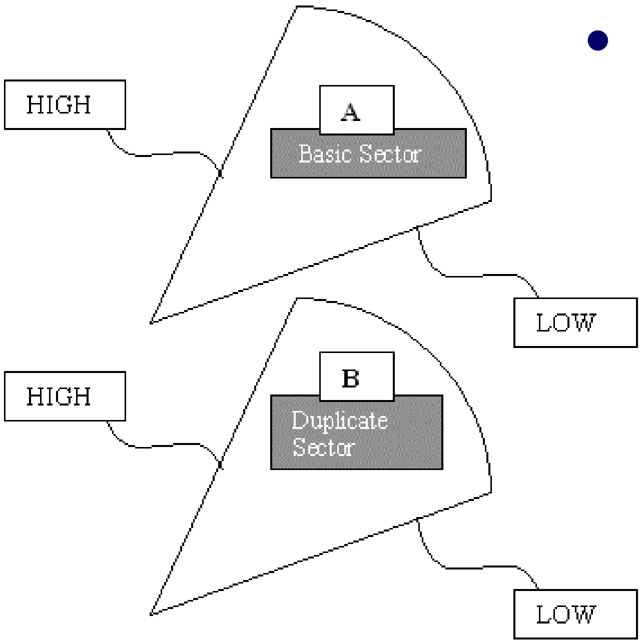
M = N/2 for even N

M = (N-1)/2 for odd N

The cyclically symmetric problem is solved on a single substructure enforcing the compatibility boundary conditions between the cyclic substructures.

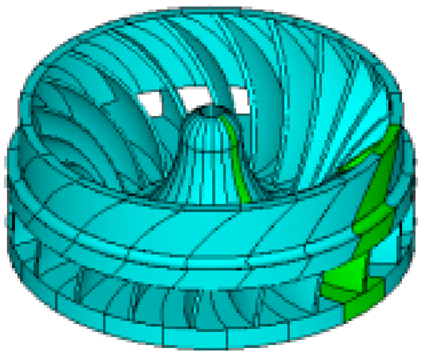
- Two most commonly employed solution methods are Duplicate Sector and Complex Hermitian
- For faster performance, ANSYS employs the Duplicate Sector method
  - Constraint equations used to enforce cyclic symmetry boundary conditions on the sector edges
- Combine the solutions (real & imaginary) from the two sectors to obtain the full structure solution

Implementation



- Basic Sector
- Low Edge / High Edge
- Duplicate Sector
- Constraint Equations

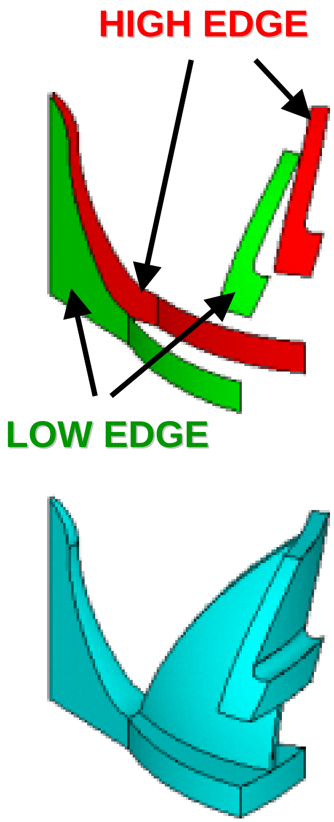
Basic Sector



BASIC
SECTOR

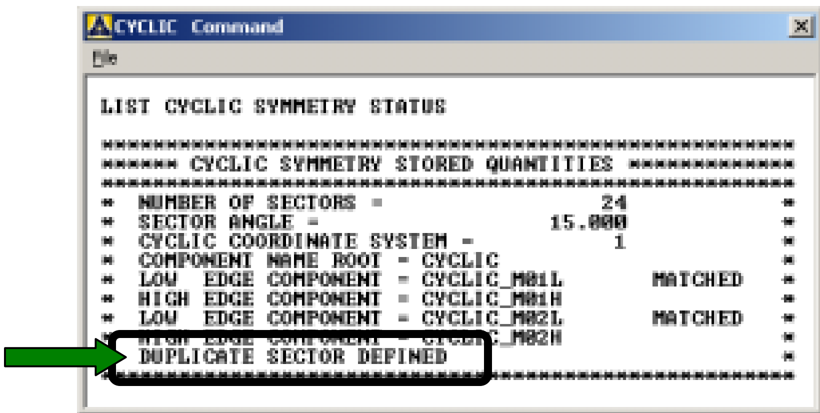
- One part of a pattern that, if repeated N times in cylindrical coordinate space, yields the complete model
- The angle θ (in degrees) spanned by the basic sector should be such that $N\theta = 360$, where N is an integer.
- Meshed or unmeshed geometry
- Nodes and elements (no geometry)
- User-defined coupling and constraint equations permitted on “internal” nodes
- Cyclic coordinate system can be any defined cylindrical system

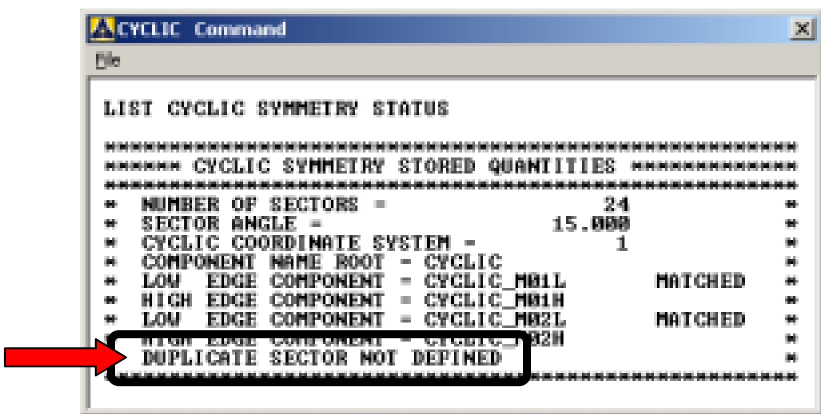
Low Edge / High Edge



- Edge having the algebraically lower θ in the R-θ-Z (cylindrical) coordinate system is called the "low edge"
- Edge having the higher θ is called the "high edge"
- Edge entities stored in components
  - Lines, areas, nodes
- Matched or unmatched node patterns
- "Internal" nodes are those not included on the low and high edges

Duplicate Sector

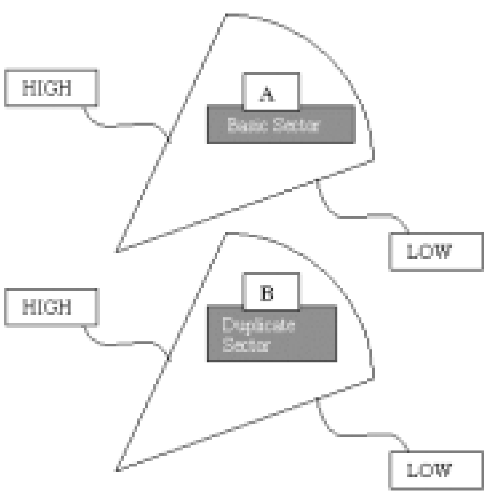




- Created automatically during solution
- Nodes and elements at same geometric location as the basic sector
- Loading, boundary conditions, and coupling and constraint equations automatically copied from the basic sector
- Option to remove the duplicate sector, however…
  - The duplicate sector is needed for displaying cyclic symmetry results in /POST1 !!

Constraint Equations

- Used to enforce cyclic symmetry boundary conditions on the sector edges
- Automatically generated during solution
- Automatically deleted after solution
- NOTE: Nodal coordinate systems of all nodes on the low and high sector edges are automatically rotated to be parallel with the cyclic coordinate system



$$\begin{Bmatrix} U_{High}^{A} \\ U_{High}^{B} \end{Bmatrix} = \begin{bmatrix} \cos k\alpha & \sin k\alpha \\ -\sin k\alpha & \cos k\alpha \end{bmatrix} \begin{Bmatrix} U_{Low}^{A} \\ U_{Low}^{B} \end{Bmatrix}$$

where,
k = nodal diameter
α = sector angle ($2\pi / N$)

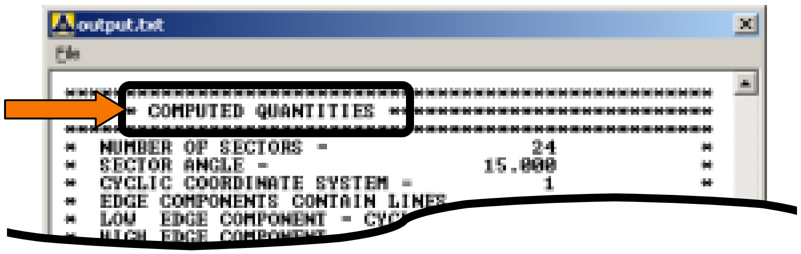
Commands

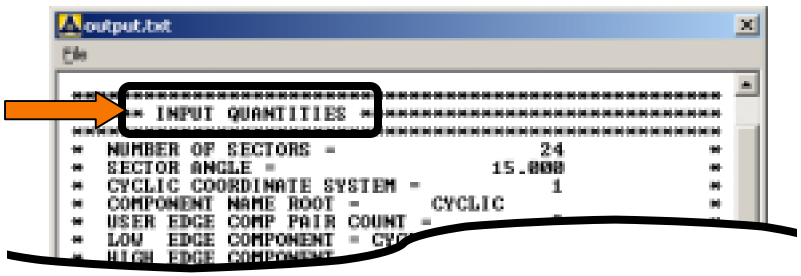
- CYCLIC
  - Configures the database for cyclic symmetry
- CYCOPT
  - Specifies cyclic symmetry solution options
- /CYCEXPAND
  - Graphically expands elements and results
- CYCPHASE
  - Determines max/min results quantities from modal analysis frequency couplets

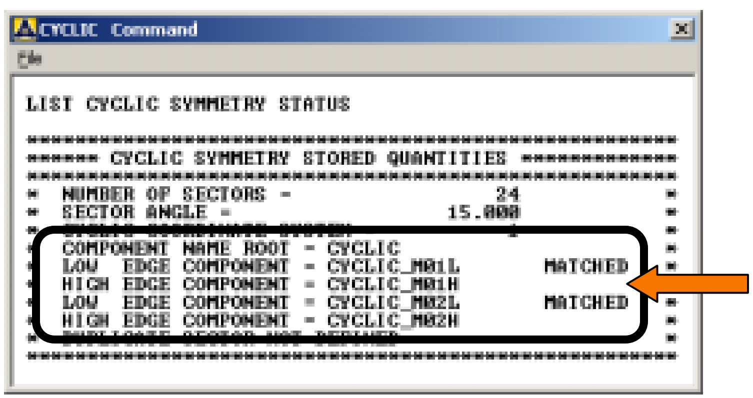
~~CYCGEN~~
~~CYCSOL~~
~~/EXPAND~~

	/PREP7	/SOLUTION	/POST1
CYCLIC	Yes	No	No
CYCOPT	Yes	Yes	No
/CYCEXPAND	Yes	No	Yes
CYCPHASE	No	No	Yes

CYCLIC







- “Automatic” mode
  - Automatically detects the number of sectors, the sector angle, and the cyclic coordinate system based upon the existing solid or finite-element model
- “Manual” mode
  - User must create and verify low and high edge component pairs
- Component names

  *name*_**m***xx***l,** name_**m***xx***h**

  *name*_**u***xx***l,** name_**u***xx***h**

  - *“m”* used for potentially matched node patterns
  - *“u”* used for potentially unmatched node patterns
  - *“name”* can contain up to 11 characters
  - *“xx”* is the component pair number starting at 01

CYCOPT

`CYCOPT,NODDIA`

- Nodal diameter solution ranges

`CYCOPT,DOF`

- Degrees of freedom (DOF's) for constraint equations from low to high edges

`CYCOPT,TOLER`

- Tolerance for matching node algorithm

`CYCOPT,MOVE`

- Move nodes to be precisely matched
- Status and default reset options
- Defaults:
  - All applicable nodal diameters solved
  - All applicable DOF's for constraint equations
  - (1e-6) X (characteristic model length) for matching node tolerance
  - Do not move edge nodes

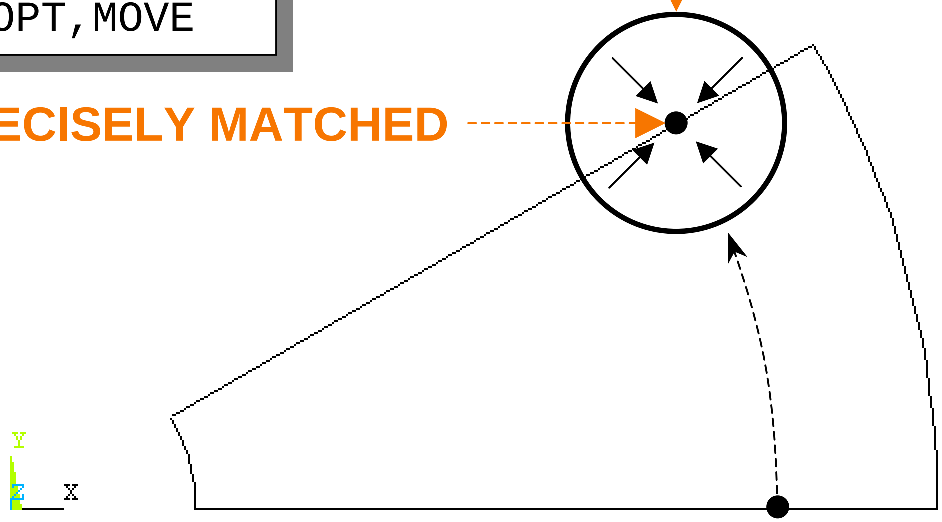
CYCOPT (continued)

TOLERANCE BOUNDARY
FOR NODE PAIRING

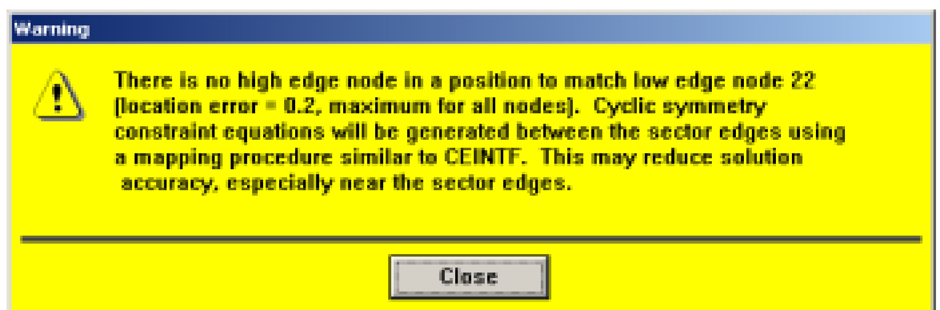
User control:
CYCOPT,MOVE

User control:
CYCOPT,TOLER

PRECISELY MATCHED



NOTE: IF ONE OR MORE “HIGH EDGE” NODES ARE OUTSIDE THE TOLERANCE SPHERE, THE UNMATCHED LOGIC IS USED AUTOMATICALLY



/CYCEXPAND

`/CYCEXPAND,,AMOUNT`	• Number of sectors to expand
`/CYCEXPAND,,WHAT`	• Element components to expand
`/CYCEXPAND,,EDGE`	• Controls for averaging across sector boundaries
`/CYCEXPAND,,PHASE`	• Phase angle shift
	• Status and default reset options

$$U_j = U^A \cos\{(j-1)k\alpha+\phi\} - U^B \sin\{(j-1)k\alpha+\phi\}$$

U_j = Response of the full structure for sector number j

U^A = Basic sector solution

U^B = Duplicate sector solution

j = Sector number

k = Nodal diameter

α = Sector angle ($2\pi/N$)

ϕ = Phase angle

CYCPHASE

`CYCPHASE,ALL`	• Maximum and minimum results for displacement, stress, and strain
`CYCPHASE,LIST`	• List max/min at each node
`CYCPHASE,PUT`	• Put max or min results on basic sector for plotting
`CYCPHASE,STAT`	• Summary status

$$U_i(\phi) = U_i^A \cos\phi - U_i^B \sin\phi$$

```
Summary of Modal Cyclic-Symmetry Phase Angle Sweep
Load Step = 3  Sub Step = 10

                      MINIMUM                                          MAXIMUM
         Node          Value      Phase Ang (DEG)  Node                 Value      Phase Ang (Deg)
 SEQV:      2           4.29534    36.0000           62           57134.22623    308.0000
```

Supported Analysis Types

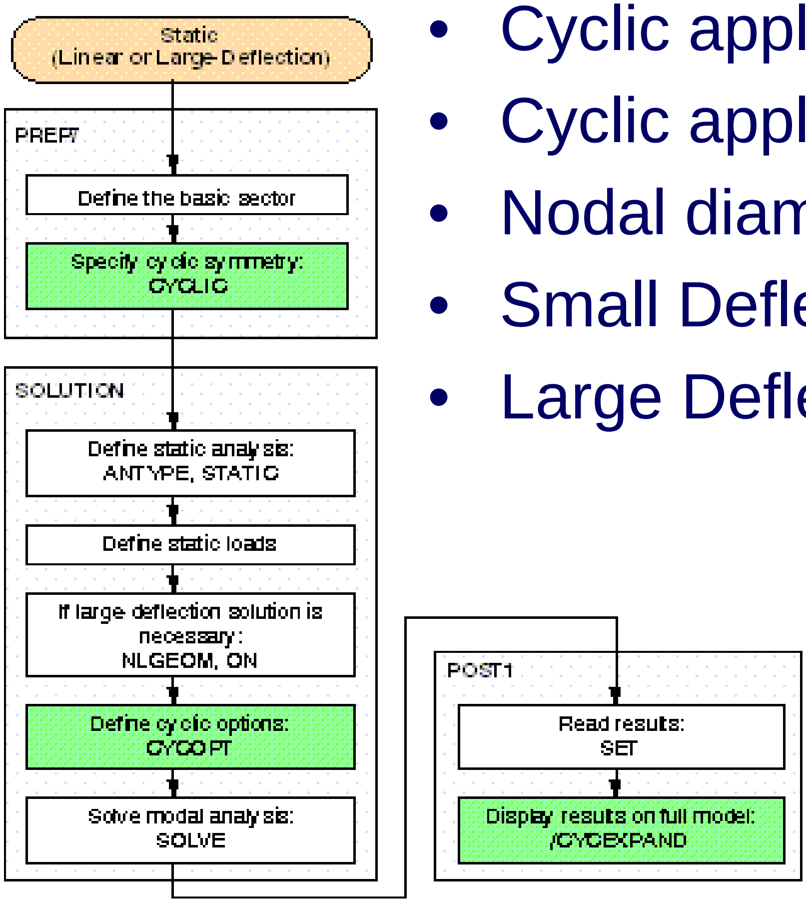
`ANTYPE,STATIC`

- STATIC Cyclic Symmetry
  (with cyclic loading only)
  – Small Deflection
  – Large Deflection

`ANTYPE,MODAL`

- MODAL Cyclic Symmetry
  – Small Deflection Stress-Free
  – Small Deflection Pre-Stressed
  – Large Deflection Pre-Stressed

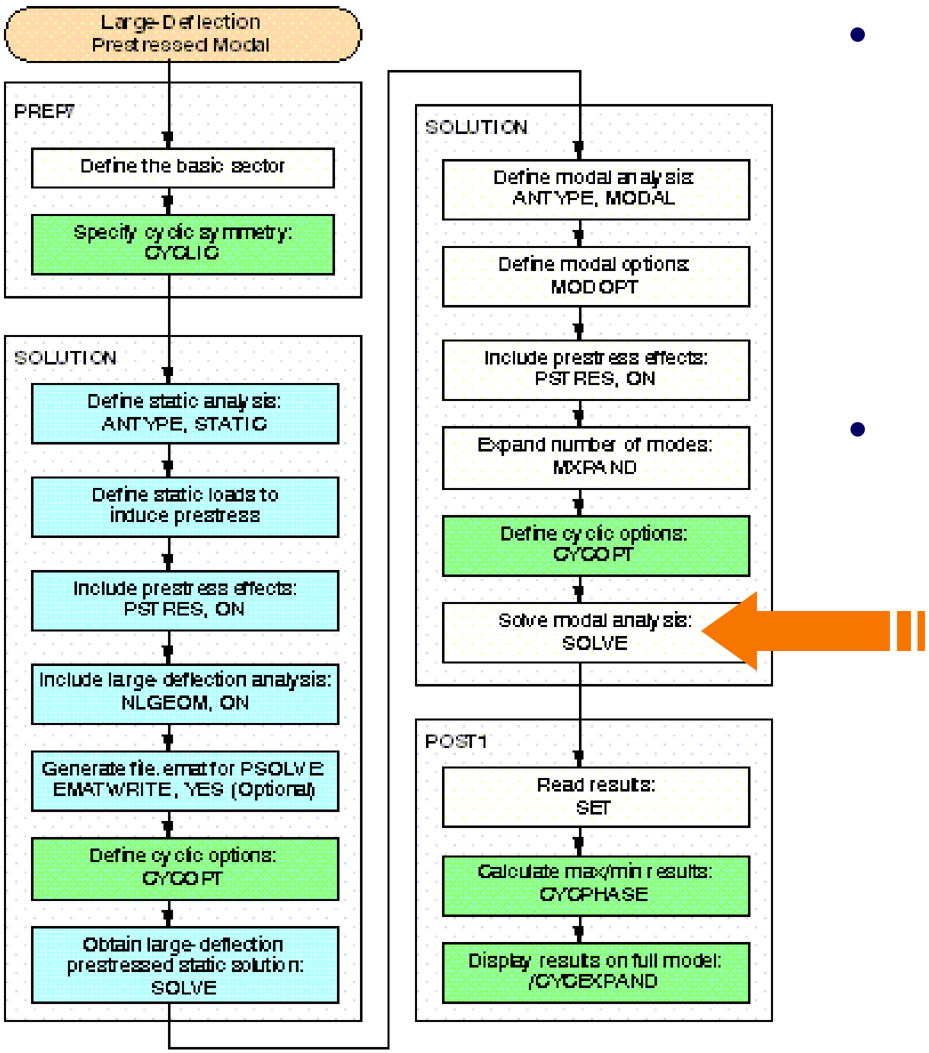
STATIC Cyclic Symmetry



- Cyclic applied loads
- Cyclic applied displacements (constraints)
- Nodal diameter zero solution
- Small Deflection
- Large Deflection

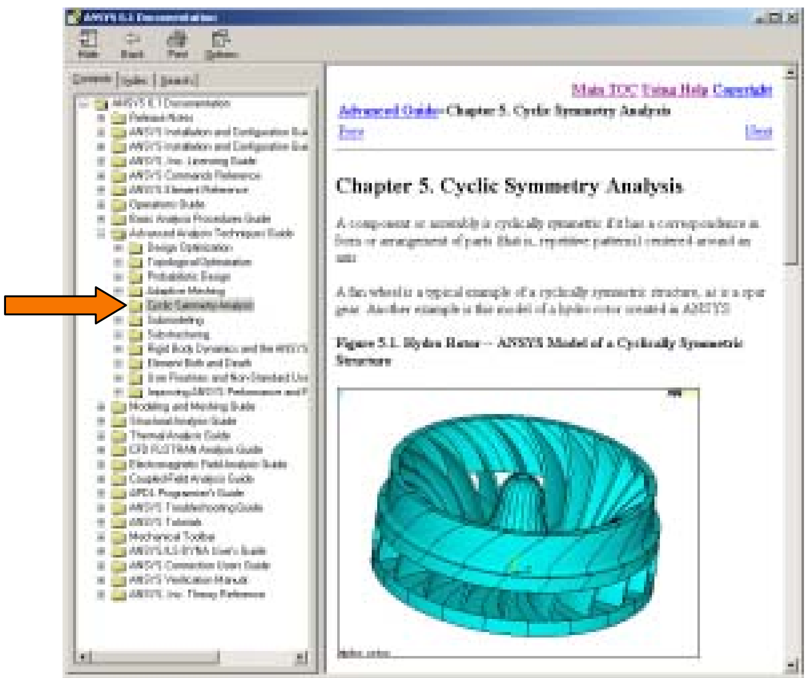
NOTE: It is recommended that this method be used instead of the CPCYC command for static cyclic symmetry.

MODAL Cyclic Symmetry



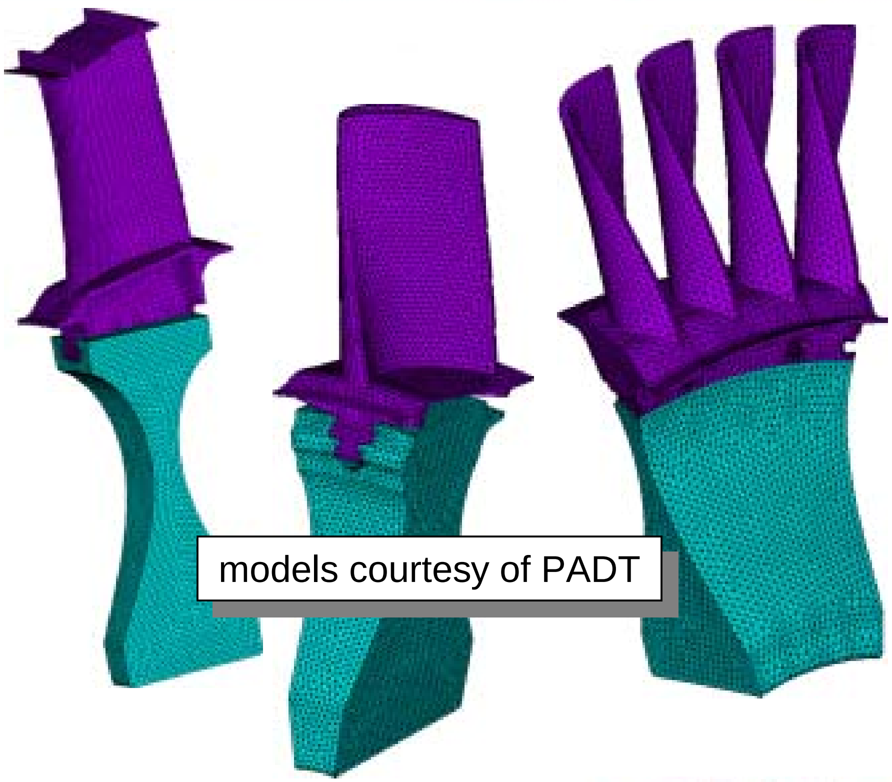
- To obtain the large deflection pre-stressed static solution:
  - Include large deflection effects with NLGEOM,ON
  - Include pre-stress effects with PSTRES,ON
- To obtain the large deflection pre-stressed modal solution, two options are available:
  1. Issue SOLVE command to update the geometry and solve
  2. Update the geometry (via the UPCOORD command) and issue the PSOLVE,EIGLANB command

Analysis Guide

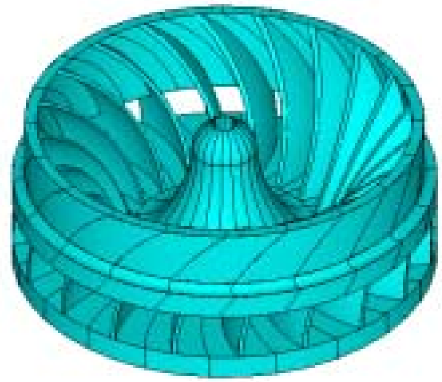


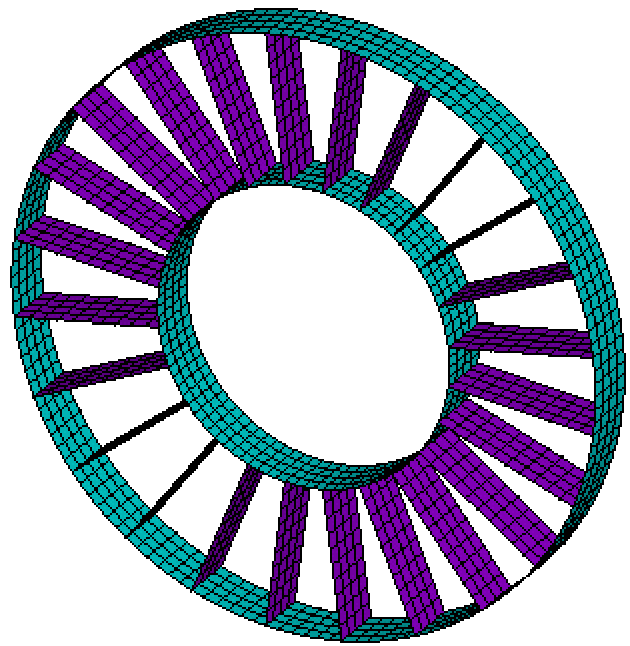
- "Cyclic Symmetry Analysis" chapter in the Advanced Analysis Techniques Guide
  - Provides central location for documentation of all supported cyclic symmetry analysis types
  - Main sections:
    - Understanding Cyclic Symmetry Analysis
    - Cyclic Modeling
    - Solving a Cyclic Symmetry Analysis
    - Post-processing a Cyclic Symmetry Analysis
  - Includes modeling process flowcharts
  - Old modal cyclic symmetry section removed from the Structural Analysis Guide (previously section 3.14 at release 6.0)

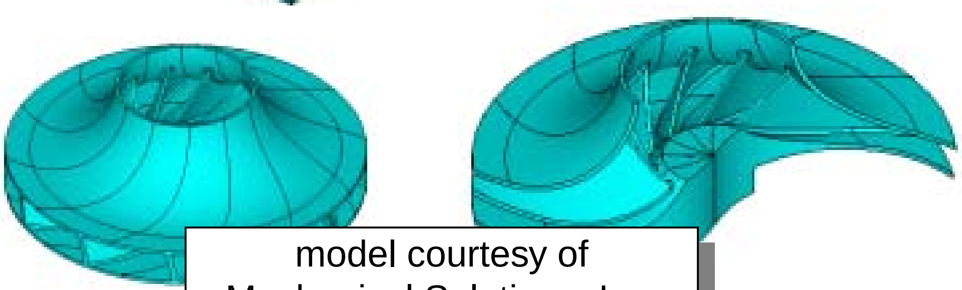
Example Models



models courtesy of PADT



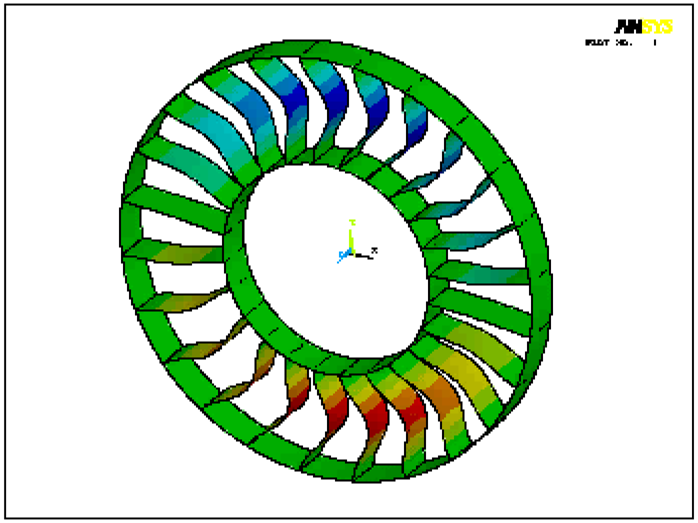




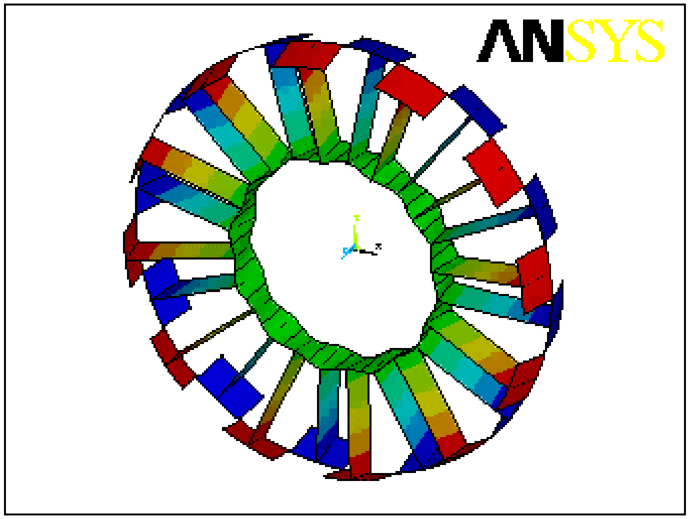
model courtesy of
Mechanical Solutions, Inc.

Example Models (continued)

/CYCEXPAND,,PHASE



CYCOPT,DOF



Future Efforts

- Static Cyclic Symmetry
  (with non-cyclic loading)

`ANTYPE,BUCKLE`

- Linear Buckling Cyclic Symmetry

`ANTYPE,HARMIC`

- Harmonic Cyclic Symmetry

`ANTYPE,TRANS`

- Transient Cyclic Symmetry
- Heat-Transfer Cyclic Symmetry

F.A.Q.'s

Q1: What is the best way to ensure precisely matched node pairs?

A1: Issue the CYCLIC command before meshing the basic sector. Subsequent AMESH and VMESH commands will attempt to automatically create precisely matched node pairs.

Q2: I am using the CYCOPT DOF option. Why do my deformed shape plots look strange?

A2: Turn off averaging across the sector boundaries using the EDGE option on the /CYCEXPAND command.

Q3: What is the correct method for removing the duplicate sector?

A3: Use the UNDOUBLE (or OFF) option on the CYCLIC command.

Q4: Why is the maximum X-stress from CYCPHASE less than the maximum X-stress from my expanded results plot using /CYCEXPAND?

A4: CYCPHASE currently has several limitations:

- The RSYS command has no effect. Component values reported by CYCPHASE are in the global Cartesian coordinate system. (However, /CYCEXPAND does support RSYS.)
- Response results are valid only for the first cyclic sector.
- Midside node values are node considered when evaluating maximum and minimum values.

Q5: There appear to be many functional and ease-of-use enhancements to cyclic symmetry but have there been any solver performance improvements?

A5: Yes, the sparse solver has been enhanced to use a symbolic equation assembly process. This offers many performance benefits for (modal) cyclic symmetry analyses which typically contain large numbers of constraint equations and by default use the sparse matrix solver and Block Lanczos eigenvalue extraction method.

Q6: Is there any way to "glue" two dissimilar meshes together in my basic sector and perform a large deflection analysis?

A6: Yes, you may use surface-to-surface bonded contact within the basic sector. The contact information is automatically copied to the duplicate sector.

F.A.Q.'s (continued)

Q7: Are there any basic sector mesh restrictions for using automatic detection on the CYCLIC command?

A7: Yes, automatic detection is valid for models meshed as follows:

- All elements meshed into volumes only
- All elements meshed into areas only (no volumes selected)
- All 3-D solid elements only (no volumes or areas selected)
- All 3-D shell elements only (no volumes or areas selected)
- All plane 2-D elements only (no volumes or areas selected).

Examples requiring manual specification include models meshed with a combination of volumes and areas, or models meshed with lines.

Q8: How can I animate a traveling wave?

A8: Use the PHASE angle option on the /CYCEXPAND command combined with the /SEG,MULTI and ANIM,,1 commands to create graphic frames at different phase angles. Refer to the following example macro:

```
/USER,1
/SEG,DELE
/SEG,MULTI
frames=arg1
angle=360/frames
*DO,phase,0,360-angle,angle
/CYCEXPAND,,PHASEANG,phase
/REPL
*ENDDO
/SEG,OFF
ANIM,,1,arg2
```