ON DYNAMICS OF SPINNING STRUCTURES

K. K. Gupta
NASA - DFRC
Edwards, California, USA

A. Ibrahim
Norfolk State University
Norfolk, Virginia, USA
aiibrahim@odu.edu

ABSTRACT

This paper provides details of developments pertaining to vibration analysis of gyroscopic systems, that involves a finite element structural discretization followed by the solution of the resulting matrix eigenvalue problem by a progressive, accelerated simultaneous iteration technique. Thus Coriolis, centrifugal and geometrical stiffness matrices are derived for shell and line elements, followed by the eigensolution details as well as solution of representative problems that demonstrates the efficacy of the currently developed numerical procedures and tools.

NOMENCLATURE

$C_C$ Coriolis acceleration matrix
$C_d$ elastic damping matrix
$K_E$ elastic stiffness matrix
$K_G$ geometric stiffness matrix
$K'$ centripetal acceleration matrix
$M$ elastic mass or inertia matrix
$N$ shape function
$f$ initial force vector
$g$ aerelastic or structural damping
$i^*$ $\sqrt{-1}$, imaginary number
$q$ displacement vector
$\dot{q}, \ddot{q}$ velocity and acceleration vectors
$u$ displacement vector

$\zeta$ damping
$\lambda$ natural frequencies
$\lambda$ structural direction cosine matrix
$\Phi$ structural modes of vibration
$\Omega$ angular velocity matrix, spin rate
$\omega$ frequencies

Superscripts
$T$ matrix transpose
$^{-1}$ matrix inverse
$^e$ elementwise

INTRODUCTION

Many practical problems, as turbines, helicopters and others are characterized by rotating components arising out of functional requirements. Others as spacecraft and satellites are often spin stabilized. Their natural frequency analysis [1] is of much importance for subsequent determination of state of stress as well for stability and control analyses. To derive the relevant equations of motion one may consider the elastic deformation $u_j$ of a point $j$ in a flexible body rotating at a constant angular velocity $\Omega$ about an arbitrary axis, having components $\Omega_X$, $\Omega_Y$, and $\Omega_Z$ along the three reference coordinate system axes (Fig. 1). Thus, the position vector may be derived as

$$ \mathbf{r} = \mathbf{r}_j + \mathbf{u}_j $$

(1)
whereas the velocity and acceleration vectors can be written as

\[ \mathbf{v} = \frac{\partial \mathbf{r}}{\partial t} + \Omega \times \mathbf{r} \]  

(2)

\[ \mathbf{a} = \frac{\partial \mathbf{v}}{\partial t} + \Omega \times \mathbf{v} \]

(3)

\[ \frac{\partial^2 \mathbf{r}}{\partial t^2} + \Omega \times \dot{\mathbf{r}} + 2\Omega \times \mathbf{v} + \mathbf{r} \times (\Omega \times \mathbf{r}) \]

respectively; further

\[ \Omega \mathbf{r} = \begin{bmatrix} 0 & -\Omega_z & \Omega_y \\ \Omega_z & 0 & -\Omega_x \\ -\Omega_y & \Omega_x & 0 \end{bmatrix} \begin{bmatrix} r_x \\ r_y \\ r_z \end{bmatrix} \]  

(4)

In Eqn. (3), the first term on the right hand side relates to the effects of in-plane stretching on out-of-plane deformation; the second term reduces to zero for steady spin state while the third and fourth terms relate to Coriolis and centripetal acceleration. The preceding equations may be conveniently used in formulating strain and kinetic energies and the governing equation of motion [2] for the entire flexible body may be derived, for the undamped case, using Hamilton's principle as

\[ \mathbf{M} \ddot{\mathbf{q}} + 2\mathbf{M} \Omega \dot{\mathbf{q}} + (\mathbf{K}_E + \mathbf{M} \Omega \Omega) \mathbf{q} = -\mathbf{M} \Omega \Omega \mathbf{r} \]  

(5)

or

\[ \mathbf{M} \ddot{\mathbf{q}} + \mathbf{C}_c \dot{\mathbf{q}} + (\mathbf{K}_E + \mathbf{K}') \mathbf{q} = \mathbf{f}_c \]  

(6)

\( \mathbf{f}_c \) being the centrifugal force vector and \( \mathbf{r} \) representing all \( \mathbf{r}_l \), \( \mathbf{M} \), \( \mathbf{K}_E \), and \( \mathbf{K}' \) are respectively the inertia, elastic and centripetal stiffness matrices, \( \mathbf{C}_c \) being the Coriolis matrix.

The related analysis starts by first computing the steady-state deflection due to constant spin \( \Omega \) by solving

\[ (\mathbf{K}_E + \mathbf{K}') \mathbf{q} = \mathbf{f}_c \]  

(7)

and thereafter calculating the geometrical stiffness matrix \( \mathbf{K}_G \) from resulting in-plane stresses. The equation of motion can then be written as below, that also includes damping

\[ \mathbf{M} \ddot{\mathbf{q}} + (\mathbf{C}_c + \mathbf{C}_d) \dot{\mathbf{q}} + (\mathbf{K}_E (l + \mathbf{i}^* g) + \mathbf{K}') \mathbf{q} = \mathbf{0} \]  

(8)

in which \( \mathbf{C}_d \) is viscous damping matrix, \( g \) is the structural damping parameter, \( \mathbf{i}^* \) being the imaginary number \( \sqrt{-1} \).

To perform relevant dynamic analysis it is essential first to derive expressions for nodal centrifugal forces for various finite elements spinning about an arbitrary axis. Such in-plane forces are used for derivation of \( \mathbf{k}_g \) matrices, where its out-of-plane components are used for developing expression for the element centripetal stiffness matrix \( \mathbf{k}_c \); examples of some of these matrices are derived next.

**NUMERICAL FORMULATION**

**Derivation of Nodal Centrifugal Forces**

Figure 1 shows a typical triangular flat shell element undergoing an uniform spin rate \( \Omega_e \) along an arbitrary axis.

Using local coordinate system (LCS) defined by \( x, y, \) and \( z \) axes, the shape function matrix \( \mathbf{N} \) for in-plane motion of the element having components along global reference axes \( X, Y, Z \), respectively.

\[ \mathbf{u} = \mathbf{N} \mathbf{u}^e \]  

(9)

where

\[ \mathbf{N} = \mathbf{R} \mathbf{Q}^{-1} \]  

(10)

and in which \( \mathbf{u} \) is the displacement vector of a typical point \( P \) within the element; \( \mathbf{u}^e \) is the element nodal displacement vector, \( \mathbf{R} \) is the portion of the shape function matrix having elements that are functions of the local coordinates \( x \) and \( y \), and \( \mathbf{Q} \) is the portion of the shape function matrix with elements expressed in terms of the element nodal coordinate values. Further defining the internal force vector at any point within the element in the LCS as
\[ \mathbf{f} = \begin{bmatrix} f_x & f_y & f_z \end{bmatrix} \]  

(11)

, the equivalent concentrated nodal forces of a triangular element in the LCS may be expressed as

\[ \mathbf{f}^e = \begin{bmatrix} f_{x1} & f_{y1} & f_{z1} & \cdots & f_{x3} & f_{y3} & f_{z3} \end{bmatrix}^T \]  

(12)

which may also be written in the following form:

\[ \mathbf{f}^e = \int_N \mathbf{N}^T \mathbf{f} \, dv \]  

(13)

or

\[ \mathbf{f}^e = \int_N \mathbf{N}^T \lambda \mathbf{p} \, dv \]  

(14)

where \( \mathbf{p} \) represents the forces in the global coordinate system at any point within an element, having three components \( p_x, p_y, \) and \( p_z \) in the \( X, Y, \) and \( Z \) directions, respectively, and \( \lambda \) is the element direction cosine matrix:

\[ \lambda = \begin{bmatrix} l_x & m_x & n_x \\ l_y & m_y & n_y \\ l_z & m_z & n_z \end{bmatrix} \]  

(15)

in which \( l_x = \cos(X, x) \), and so on. Furthermore, defining \( X_i, Y_i, \) and \( Z_i \) as the global coordinates of node \( i \) of the triangular element, such coordinates for any point within the element may simply be obtained as

\[ \begin{bmatrix} X \\ Y \\ Z \end{bmatrix} = \begin{bmatrix} X_i \\ Y_i + \lambda_y Y \\ Z_i \end{bmatrix} \]  

(16)

The in-plane element nodal centrifugal forces may next be derived for each of the three components of the spin rate \( \Omega_x \) which may then be combined to yield the final desired expressions. Thus, typically, corresponding the spin component \( \Omega_x \), the appropriate forces are expressed as

\[ \mathbf{p} = \rho \Omega_x^2 \begin{bmatrix} 0 \\ Y \\ Z \end{bmatrix} \]  

(17)

where \( \rho \) is the mass density. Upon the employment of the relationships expressed by Eqns. (15) and (16), Eqn. (17) takes the following form:

\[ \mathbf{p} = \rho \Omega_x^2 \begin{bmatrix} 0 \\ m_x x + m_y y + Y_i \\ n_x x + n_y y + Z_i \end{bmatrix} \]  

(18)

Expressions for the element nodal forces is then derived by appropriate substitution of Eqns. (10), (15), and (18) into Eqn. (14), yielding

\[ \mathbf{f}^e(\Omega_x) = \rho \Omega_x^2 \left[ \mathbf{Q}^{-1} \right] \int_{x_k}^{x_h} \int_{y_k}^{y_h} \mathbf{R} \, dx \, dy \]  

(19)

where \( t \) is the element thickness, \( y_k \) is the \( y \) coordinate of node \( k \), \( x_k = x_k y / y_k \) is the lower bound of the \( x \) coordinate in the integration process, \( x_h = x_j - (x_j - x_k) y / y_k \) is the upper bound of the \( x \) coordinate, and

\[ \chi = \begin{bmatrix} m_x (m_x x + m_y y + Y_i) + n_x (n_x x + n_y y + Z_i) \\ m_y (m_x x + m_y y + Y_i) + n_y (n_x x + n_y y + Z_i) \end{bmatrix} \]  

(20)
In Eqn. (19) the vector \( f^e_p \) contains the in-plane element nodal forces in local \( x \) and \( y \) directions, being expressed as 
\[
\begin{bmatrix}
f_{x_i}\ f_{y_i}\ f_{x_j}\ f_{y_j}\ f_{x_k}\ f_{y_k}
\end{bmatrix}^T.
\]

Associate forces due to spin rates in the \( Y \) and \( Z \) directions may also be similarly expressed as
\[
f^e_p(\Omega_y) = \rho \Omega_z^2 \int_0^{x_i} \int_0^{y_i} R^e \gamma dxdy
\]
\[
f^e_p(\Omega_z) = \rho \Omega_z^2 \int_0^{x_i} \int_0^{y_i} R^e \xi dxdy
\]
where
\[
\gamma = \begin{bmatrix}
l_x (l_x x + l_y y + X_i) + n_x (n_x x + n_x y + Z_i)
l_y (l_x x + l_y y + X_i) + n_y (n_x x + n_x y + Z_i)
\end{bmatrix}
\]
(23)
\[
\xi = \begin{bmatrix}
l_x (l_x x + l_y y + X_i) + m_x (m_x x + m_x y + Z_i)
l_y (l_x x + l_y y + X_i) + m_y (m_x x + m_x y + Z_i)
\end{bmatrix}
\]
(24)

The total element in-plane nodal forces are simply combined as
\[
f^e_p = f^e_p(\Omega_x) + f^e_p(\Omega_y) + f^e_p(\Omega_z)
\]
and may next be transformed into the global coordinate system (GCS) as
\[
f^e_p = \lambda^T f^e_p
\]
for subsequent stress analysis and generation of the \( k_G \) matrix.

The out-of-plane components of an element centrifugal force vector may be derived similarly. Then, the element centrifugal force matrices can be readily formulated as
\[
K^e(\Omega_x) = \Omega_x^2 \left( n_x^2 + m_x^2 \right)\mathbf{M}
\]
(27)
\[
K^e(\Omega_y) = \Omega_y^2 \left( n_y^2 + l_y^2 \right)\mathbf{M}
\]
(28)

\[
K^e(\Omega_z) = \Omega_z^2 \left( n_z^2 + m_z^2 \right)\mathbf{M}
\]
(29)

\( \mathbf{M} \) being the inertia matrix and the complete expression for the global centrifugal force matrix is obtained simply as
\[
K^e = K^e(\Omega_x) + K^e(\Omega_y) + K^e(\Omega_z).
\]

For quadrilateral elements, such data as derived from four constituent triangular elements by suitably combining them in an orderly fashion.

\textbf{Figure 2 A line element with an arbitrary spin rate}

For a line element (Fig. 2), the coordinate at any point within the element is obtained as
\[
\begin{bmatrix}
X
Y
Z
\end{bmatrix} = \begin{bmatrix}
X_i
Y_i
Z_i
\end{bmatrix} + \lambda^T \begin{bmatrix}
u_x
u_y
u_z
\end{bmatrix}
\]
(30)
in which \( u_x \) and \( u_z \) are deformations at any point on the element in the local \( y \) and \( z \) directions respectively.

Proceeding as in the case of shell elements and assuming nodal lumped masses \( m_i \), the centrifugal forces at a typical \( i \)th node expressed in global coordinate system.

\[
p_i^x = m_i \Omega_x^2 X_i + m_i \Omega_z^2 X_i
\]
(31)
\[
p_i^y = m_i \Omega_y^2 Y_i + m_i \Omega_z^2 Y_i
\]
(32)
\[
p_i^z = m_i \Omega_z^2 Z_i + m_i \Omega_z^2 Z_i
\]
(33)
The element centripetal and geometric stiffness matrices may then be derived as before.

**Coriolis Acceleration Matrix**

For any structural element such a matrix can be derived as follows

\[ C^c_C = 2M^c\Omega^c \]  
\[ \text{(34)} \]

in which the element inertia matrix \( M^c \) in calculated by employing standard formulation

**Free Vibration of Spinning Bodies**

The associated matrix equation of undamped motion of a flexible spinning body, discretized by the finite element method, can be derived from Eqn. (8) as

\[ Kq + Cq + M\ddot{q} = 0 \]  
\[ \text{(35)} \]

in which \( K = K_E + K^c + K_G \) is the stiffness matrix, \( C = C_C \) the Coriolis force matrix, and \( M \) is the inertia matrix. For small vibration the matrices \( K \) and \( M \) are real, symmetric and positive definite, whereas \( C_C \) is skew symmetric, being also a function of the spin \( \Omega \). Eqn. (35) may be resolved into a set of first-order ordinary differential equation as below resulting in a linear eigenvalue problem.

\[ Ay + B\dot{y} = 0 \]  
\[ \text{(36)} \]

in which

\[ A = \begin{bmatrix} M & 0 \\ 0 & K \end{bmatrix}, \quad B = \begin{bmatrix} 0 & -M \\ M & C \end{bmatrix}, \quad y = \begin{bmatrix} q \\ \dot{q} \end{bmatrix} \]  
\[ \text{(37)} \]

The matrices \( A \) and \( B \) are of order \((2 \times N)\), \( N \) being order of \( K, M, \) and \( C \) matrices, noting that \( B \) is skew-symmetric. Solution of Eqn. (36) may be assumed as \( y = \phi e^{\omega t} \) yielding

\[ (A + \omega B)\phi = 0 \]  
\[ \text{(38)} \]

where the eigenvalues \( \omega \) are pure imaginary, the eigenvectors occurring in complex conjugate pairs. Eqn. (38) may be further rearranged [3] as

\[ (A - \lambda F)\phi = 0 \]  
\[ \text{(39)} \]

in which \( F = i^*B \) and can also be expressed in expanded form

\[ \begin{bmatrix} M & 0 \\ 0 & K \end{bmatrix} - \lambda \begin{bmatrix} i^*M & i^*C \\ i^*M & i^*C \end{bmatrix} \begin{bmatrix} \Psi \\ \dot{\Psi} \end{bmatrix} = 0 \]  
\[ \text{(40)} \]

where \( F \) is a pure Hermitian matrix, the roots \( \lambda = i^*\omega \) are real and occur in pairs \( \lambda_1, -\lambda_1, \ldots, \lambda_N, -\lambda_N \), associated eigenvectors occurring in complex conjugate pairs. Eigenvalues of the original Eqn. (38) may simply be obtained as \( \lambda/i^* \), while noting that eigenvectors are the same for both the cases.

Solution of Eqn. (39) has been achieved earlier by various solution techniques [3,4,5]. A variant of the multivector progressive iteration technique [6,7,8] is presented next.

**Eigensolution by a Progressive multivector Iteration**

Equations (38) and (39) are used for the computation of the first \( NR \) roots and vectors. Associated solution steps are given next:

Step 1. Perform Cholesky factorization of the real symmetric and positive definite matrix \( A \) of order \( 2N \times 2N \), taking into account the sparsity of the constituent matrices, initially only.

\[ A = LDL^T \]  
\[ \text{(41)} \]

\( L \) is an unit lower triangular matrix, \( D \) being diagonal matrix.

Step 2. Form a set of randomly generated \( 2 \times NRT \) (\( NRT > NR \)) real, trial vectors each of order \( 2N \), \( NRT \) being number of trial vectors.

\[ \begin{bmatrix} \hat{x}_1 & \hat{y}_1 & \hat{x}_2 & \hat{y}_2 & \ldots & \hat{x}_{NRT} & \hat{y}_{NRT} \end{bmatrix} \]  
\[ \text{(42)} \]

where

\[ i\hat{\phi} = i\hat{x} + i^*\hat{y}, \quad i^* = \sqrt{-1} \]  
\[ \text{(43)} \]

Step 3. Initially form
\[ \hat{\mathbf{x}}_i = \begin{bmatrix} \hat{x}_1 & \hat{x}_2 & \cdots & \hat{x}_{\text{NRT}} \end{bmatrix} \] (44)

Step 4. Using only unconverted roots, solve
\[ A Y_{i+1} = B \hat{\mathbf{x}}_i \] (45)

or in individual matrix form
\[ K Y_{i+1}^{(l)} = M \hat{\mathbf{x}}_i^{(l)} + C \hat{\mathbf{x}}_i^{(l)} \] (46)

yielding \( Y_{i+1}^{(l)} \)
\[ M Y_{i+1}^{(u)} = -M \hat{\mathbf{x}}_i^{(l)} \] (47)

that is
\[ Y_{i+1}^{(u)} = -\hat{\mathbf{x}}_i^{(l)}. \]

Similarly solve
\[ A X_{i+1} = B Y_{i+1} \] (48)

which can be elaborated as below
\[ K X_{i+1}^{(l)} = M Y_{i+1}^{(u)} + C Y_{i+1}^{(l)} \] (49)

yielding \( X_{i+1}^{(l)} \) and also
\[ M X_{i+1}^{(u)} = -M Y_{i+1}^{(l)} \] (50)

from which
\[ X_{i+1}^{(u)} = -Y_{i+1}^{(l)} \]

In above the superscripts \( u \) and \( l \) refer the upper and lower half of a vector, respectively.

Step 5. Using unconverted vectors only, perform vector norm check by computing an estimate of the magnitude of a typical vector as
\[ \hat{\lambda}_{i+1} = \frac{1}{\left\| x_{i+1} \right\|} \left\| x_{i+1} \right\| \] (51)

and check root convergence if
\[ \left| \hat{\lambda}_{i+1} - \hat{\lambda}_i \right| \leq \text{EPSN} \]

with \( \hat{\lambda}_i \) a prescribed convergence parameter. Assuming that first \( \text{NRI} \) roots have converged, if \( \text{NRI} = \text{NR} \), proceed to step 8.

Step 6. Setting \( p = ^1 x, \quad p = ^2 y, \quad p = ^3 x, \quad p = ^4 y, \ldots \), orthonormalize each \( \hat{p}_{i+1}^{(l)} \) vector with respect to the \( A \) matrix, only for unconverted \( \text{(NR1-NR)} \) vectors, yielding \( \hat{p}_{i+1} \), as follows:

\[ \hat{p}_{i+1}^{(l)} = \hat{p}_{i+1}^{(l)} - \frac{2 \sum_{j=1}^{\text{NRI}} \left[ \left( \hat{p}_{i}^{(l)} \right)^T A \hat{p}_{i+1}^{(l)} \right] \hat{p}_{i}^{(l)}}{\sum_{j=1}^{\text{NRI}} \left[ \left( \hat{p}_{i}^{(l)} \right)^T A \hat{p}_{i+1}^{(l)} \right]^2} \]

\[ \hat{p}_{i+1} = \hat{p}_{i+1}^{(l)} / \left[ \left( \hat{p}_{i}^{(l)} \right)^T A \hat{p}_{i+1}^{(l)} \right]^{1/2} \]

\[ j = 2 \times \text{NR1} + 1, \quad 2 \times \text{NRT} \]

Then set back \( ^1 \hat{x} = \hat{p}_1, \quad ^2 \hat{x} = \hat{p}_2, \quad ^3 \hat{x} = \hat{p}_3, \quad ^4 \hat{x} = \hat{p}_4 \), and so on.

Step 7. Go to step 4 to continue iteration till solution convergence is achieved, in which
\[ \hat{\mathbf{x}}_{i+1} = \begin{bmatrix} \text{NRI} & \hat{x}_{i+1} \end{bmatrix} \begin{bmatrix} \text{NRI} \end{bmatrix} \begin{bmatrix} \text{NRT} \end{bmatrix} \hat{\mathbf{x}}_{i+1} \] (53)

Step 8. The Rayleigh-Ritz method, involving only the unconverted roots, is employed next to solve the further reduced eigenvalue problem
\[ \hat{\Lambda}_{i+1} \hat{Q}_{i+1} = \hat{F}_{i+1} \hat{Q}_{i+1} \hat{\Lambda} \] (54)

in which
\[ \hat{\Lambda}_{i+1} = \hat{\Phi}_{i+1}^T \hat{\Lambda} \hat{\Phi}_{i+1}, \quad \hat{F}_{i+1} = \hat{\Phi}_{i+1}^T \hat{F} \hat{\Phi}_{i+1} \] (55)

with
\[ \hat{\Phi}_{i+1} = \begin{bmatrix} \text{NRI} & \hat{\phi}_{i+1} \end{bmatrix} \begin{bmatrix} \text{NRI} \end{bmatrix} \begin{bmatrix} \text{NRT} \end{bmatrix} \hat{\phi}_{i+1} \] (56)

\( \hat{\Lambda} \) being an approximation of \( \Lambda \), the diagonal matrix containing the eigenvalues.

Step 9. A root convergence test is then performed on each unconverted root under consideration,
\[ \left| \hat{\lambda}_{i+1} - \hat{\lambda}_i \right| \leq \text{EPS} \]

in which \( \text{EPS} \) is the root convergence factor.
Step 10. Recompute the eigenvectors,
\[ \tilde{\Phi}_{i+1} = \hat{\Phi}_{i+1} Q_{i+1} \]  
(58)
and relabel \( \tilde{\Phi}_{i+1} \) as \( \hat{\Phi}_{i+1} \) for possible use in step 4 involving \( \tilde{X}_{i+1} \) components of \( \hat{\Phi}_{i+1} \).

Step 11. Goto step 4 and perform steps 4, 6, 8-10 only if the number of converged roots \( N_{R1} < N_{R} \). Otherwise go to step 12.

Step 12. End of analysis.

The analysis procedure described herein enables effective computation of the first few roots and vectors which are often the requirement for the important subsequent stability and dynamic response analyses. For further references, steps 4-7, that involves checking root norm convergence, will be referred to as phase 1 operation. Subsequent phase 2 operations, involving Rayleigh-Ritz root convergence calculations consist of step 4, 6, and 8-11. Thus, progressive saving in solution time is obtained in the following key areas. (a) back substitution operation in step 4, (b) vector norm check process in step 5, (c) mass orthonormalization calculation in step 6, (d) Rayleigh Triple matrix multiplication in step 8, (e) Rayleigh vector computation in step 9. It may be noted that all major computations in steps 1-7 are performed in real number thereby saving considerable computational efforts. Solution accuracy factors for \( E_{PSN} \), \( EPS \), and \( EPSR \) are set to 0.05, 0.00001 and 0.00001, respectively.

**NUMBERICAL EXAMPLES**

Three example problems are presented next that testifies to the applicability and efficacy of the currently developed solution algorithms for computation of roots and modes of rotating bodies. The first example relates to a spinning cantilever beam subjected to an arbitrary spin rate. Results are presented for both the undamped beam as well as solutions in the presence of viscous and structural damping. The second and third example problems pertain to a rotating cantilever plate, involving rather large degrees of freedom. Solution results and CPU times are compared for the usual and the accelerated version of the associated code.

1. **Spinning Cantilever Beam**

Figure 3 shows a cantilever beam spinning about an arbitrary axis. Associated data parameters, in consistent British units, are as follows:

- Young's modulus, \( E \) = \( 30 \times 10^6 \) MPa
- Cross-sectional area, \( A \) = 1.0 m²
- Moment of inertia,
  - about \( y \) axis = 1/12 kg m²
  - about \( z \) axis = 1/24 kg m²
- Mass density, \( \rho \) = 1600 kg/m³
- Length, \( L \) = 60.0 m
- Scalar nodal viscous damping = 0.6283 (in \( x, y, z \) translations)
- Structural damping coefficient = 0.01
- Spin rate along \( Y \) axis (\( \Omega_y \)) = 0.1 rad/s

Figure 3 Spinning cantilever beam

Figure 4 depicts the first few mode shapes.

Figure 4 First few mode shapes for a cantilever beam

\( \Omega_y = 0 \)

Table 1 lists the natural frequencies of the cantilever beam with various forms of damping.
Table 1 Natural frequencies of a spinning cantilever beam

<table>
<thead>
<tr>
<th>Mode</th>
<th>Mode number</th>
<th>Natural frequencies, $\lambda$ (rad/sec)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$\Omega_r = 0$</td>
<td>$\Omega_r = 0.6283$ (rad/sec)</td>
</tr>
<tr>
<td></td>
<td>undamped</td>
<td>Viscous damping</td>
</tr>
<tr>
<td>1</td>
<td>$2.6631 \pm 2.7626$</td>
<td>$-0.3799 \pm i2.7365$</td>
</tr>
<tr>
<td>2</td>
<td>$3.7660 \pm 3.7932$</td>
<td>$-0.3800 \pm i3.7742$</td>
</tr>
<tr>
<td>3</td>
<td>$16.5039 \pm 18.8409$</td>
<td>$-0.3872 \pm i16.6360$</td>
</tr>
<tr>
<td>4</td>
<td>$23.3387 \pm 23.7476$</td>
<td>$-0.3870 \pm i23.7441$</td>
</tr>
<tr>
<td>5</td>
<td>$45.7488 \pm 47.0130$</td>
<td>$-0.3937 \pm i43.6110$</td>
</tr>
<tr>
<td>6</td>
<td>$64.6946 \pm 66.3958$</td>
<td>$-0.3933 \pm i66.3944$</td>
</tr>
<tr>
<td>7</td>
<td>$88.7152 \pm 92.0851$</td>
<td>$-0.4012 \pm i92.0840$</td>
</tr>
<tr>
<td>8</td>
<td>$125.4547 \pm 130.0557$</td>
<td>$-0.4005 \pm i130.0550$</td>
</tr>
<tr>
<td>9</td>
<td>$145.0221 \pm 152.3365$</td>
<td>$-0.4105 \pm i152.3367$</td>
</tr>
<tr>
<td>10</td>
<td>$205.0799 \pm 215.0823$</td>
<td>$-0.4093 \pm i215.0817$</td>
</tr>
</tbody>
</table>

It may be noted that for the undamped spinning cases as well as in the presence of structural damping the roots occur in pairs as $\lambda_1, -\lambda_1, \lambda_2, -\lambda_2, \ldots, \lambda_N, -\lambda_N$, the latter being also complex in nature. For the viscous damping case the roots are in complex conjugate form $(-\alpha \pm i\beta)$, whereas when the viscous and structural damping are combined, the real part tends to be somewhat different corresponding to identical imaginary parts, while also noting that the roots of the original set of Eqn. (30) are defined as $\omega = \lambda / \tau^*$. Note: lump mass option for non-spinning cases, consistent mass option for spinning cases.

2. Spinning Plate 1

A square plate (Fig. 5), cantilevered at the base is discretized by a 20x20 mesh, and analyses are conducted for spin rates along four sets of local axes ($\Omega_x$, $\Omega_y$, $\Omega_z$, and $\Omega_R$). The spin rate along an arbitrary axis, $\Omega_R$ (at 45° of each axis) = 100 rad/sec, with an input of $\Omega_x = \Omega_y = \Omega_z = 57.735$ rad/sec; also 100 rad/sec for individual axis spin rates along $x$, $y$, and $z$ local axes. Associated data parameters, in consistent British units, are as follows:

- Young’s modulus, $E$ = $10 \times 10^6$
- Side length, $L$ = 10.0
- Thickness, $t$ = 0.1
- Poisson’s ratio, $\mu$ = 0.3
- Mass density, $\rho$ = $0.259 \times 10^{-3}$

![Figure 5 Spinning cantilever plate](image-url)
Results of these analyses are summarized in Table 2. The first 12 frequencies are given in the table; first few mode shapes are also shown in Fig. 6.

![Mode 1](image1.png) ![Mode 2](image2.png) ![Mode 3](image3.png) ![Mode 4](image4.png) ![Mode 5](image5.png) ![Mode 6](image6.png)

**Figure 6 First 6 mode shapes for a cantilever plate (Ω = 0)**

<table>
<thead>
<tr>
<th>Mode</th>
<th>Non spinning (Ω = 0)</th>
<th>Ω₂ = 100</th>
<th>Ω₅ = 100</th>
<th>Ω₆ = 100</th>
<th>Ω₇ = 100</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>216.80</td>
<td>245.20</td>
<td>162.02</td>
<td>126.19</td>
<td>51.73</td>
</tr>
<tr>
<td>2</td>
<td>529.15</td>
<td>549.78</td>
<td>515.09</td>
<td>497.29</td>
<td>496.24</td>
</tr>
<tr>
<td>3</td>
<td>1325.91</td>
<td>1350.84</td>
<td>1331.52</td>
<td>1333.44</td>
<td>1309.70</td>
</tr>
<tr>
<td>4</td>
<td>1689.95</td>
<td>1703.87</td>
<td>1690.48</td>
<td>1681.95</td>
<td>1685.67</td>
</tr>
<tr>
<td>5</td>
<td>1922.04</td>
<td>1943.08</td>
<td>1928.36</td>
<td>1928.88</td>
<td>1913.21</td>
</tr>
<tr>
<td>6</td>
<td>3352.53</td>
<td>3367.97</td>
<td>3358.46</td>
<td>3357.42</td>
<td>3350.10</td>
</tr>
<tr>
<td>7</td>
<td>3810.79</td>
<td>3835.60</td>
<td>3823.53</td>
<td>3830.02</td>
<td>3804.62</td>
</tr>
<tr>
<td>8</td>
<td>3970.11</td>
<td>3981.71</td>
<td>3974.04</td>
<td>3988.21</td>
<td>3972.17</td>
</tr>
<tr>
<td>9</td>
<td>4401.49</td>
<td>4422.87</td>
<td>4412.28</td>
<td>4415.73</td>
<td>4398.49</td>
</tr>
<tr>
<td>10</td>
<td>5732.01</td>
<td>5744.32</td>
<td>5737.70</td>
<td>5735.50</td>
<td>5732.96</td>
</tr>
<tr>
<td>11</td>
<td>5993.17</td>
<td>6012.35</td>
<td>6003.40</td>
<td>6006.02</td>
<td>5992.21</td>
</tr>
<tr>
<td>12</td>
<td>7375.74</td>
<td>7397.47</td>
<td>7388.79</td>
<td>7393.43</td>
<td>7374.15</td>
</tr>
</tbody>
</table>

**Table 2 Natural frequencies (ω in rad/sec) of a spinning cantilever plate (20 x 20) (consistent mass option)**

3. **Spinning Plate 2**

In an effort to compare the efficacy of the accelerated progressive, process over the original simultaneous iterative technique, another plate (Fig. 7) that results in a rather larger order problem is analyzed next. Associate details of the plate, expressed in British units, are as follows:

- Side length, \( L \) = 30.0
- FE mesh = 30 x 30
- Spin rate, \( (\Omega_z) \) = 100 rad/sec

![Cantilever plate (30x30) spinning along Z-axis](image7.png)

**Figure 7 Cantilever plate (30x30) spinning along Z-axis**

Other details are as in the previous plate example problem. The results in a 5400 degrees of freedom problem and the relevant eigensolutions are effected using the current progressive simultaneous iterative solution method as well as the original simultaneous iterative solution; this affords a quantitative comparison of the two analysis procedures. Each eigensolution is derived to compute the first 100 modes and roots using 110 randomly generated trial vectors. For both solutions, 8 steps were needed to achieve convergence in phase 1 and another 10 steps were needed in phase 2 to achieve a final solution convergence. Table 3 provides a list of first few frequencies, for both spinning and non-spinning cases.
Table 3 First 20 natural frequencies ($\lambda$ in rad/sec) of a 30x30 spinning plate (consistent mass option)

<table>
<thead>
<tr>
<th>Mode</th>
<th>$\Omega = 0$</th>
<th>$\Omega = 100$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>24.1007</td>
<td>109.2439</td>
</tr>
<tr>
<td>2</td>
<td>58.9329</td>
<td>131.7314</td>
</tr>
<tr>
<td>3</td>
<td>147.6217</td>
<td>210.4748</td>
</tr>
<tr>
<td>4</td>
<td>188.3865</td>
<td>310.7209</td>
</tr>
<tr>
<td>5</td>
<td>214.3126</td>
<td>347.9099</td>
</tr>
<tr>
<td>6</td>
<td>374.5417</td>
<td>414.7329</td>
</tr>
<tr>
<td>7</td>
<td>424.7105</td>
<td>519.2821</td>
</tr>
<tr>
<td>8</td>
<td>443.5959</td>
<td>573.6855</td>
</tr>
<tr>
<td>9</td>
<td>491.2739</td>
<td>647.7871</td>
</tr>
<tr>
<td>10</td>
<td>641.6125</td>
<td>734.3848</td>
</tr>
<tr>
<td>11</td>
<td>670.5685</td>
<td>816.0489</td>
</tr>
<tr>
<td>12</td>
<td>824.2067</td>
<td>902.8594</td>
</tr>
<tr>
<td>13</td>
<td>858.9417</td>
<td>961.7461</td>
</tr>
<tr>
<td>14</td>
<td>890.9186</td>
<td>997.2900</td>
</tr>
<tr>
<td>15</td>
<td>962.1829</td>
<td>1145.9511</td>
</tr>
<tr>
<td>16</td>
<td>1033.7387</td>
<td>1180.3106</td>
</tr>
<tr>
<td>17</td>
<td>1089.4643</td>
<td>1276.6296</td>
</tr>
<tr>
<td>18</td>
<td>1358.6855</td>
<td>1387.4648</td>
</tr>
<tr>
<td>19</td>
<td>1377.8232</td>
<td>1440.7086</td>
</tr>
<tr>
<td>20</td>
<td>1381.0980</td>
<td>1476.7978</td>
</tr>
</tbody>
</table>

Analyses were conducted for two combinations of progressive features; Table 4 presents relevant details. These data indicates that the progressive method is more efficient than the usual simultaneous iteration technique.

Table 4 Solution details for a 30x30 spinning plate (T: true, F: false for progressive feature)

<table>
<thead>
<tr>
<th>Computation Phase</th>
<th>PSF</th>
<th>Si^2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Phase 1</td>
<td>T</td>
<td>F</td>
</tr>
<tr>
<td>Phase 2</td>
<td>T</td>
<td>F</td>
</tr>
<tr>
<td>Iteration Steps in Phase 1</td>
<td>7</td>
<td>8</td>
</tr>
<tr>
<td>Iteration Steps in Phase 2</td>
<td>11</td>
<td>11</td>
</tr>
<tr>
<td>CPU time (sec)</td>
<td>78.17</td>
<td>141.79</td>
</tr>
</tbody>
</table>

CONCLUDING REMARKS

The paper presents the novel derivations of constituent Coriolis, centrifugal and geometrical stiffness matrices for various finite elements undergoing rotation along arbitrary axes. This is followed by the matrix formulation of the associated equation of motion, which proves to be convenient for subsequent natural frequency analysis. An accelerated simultaneous iteration solution method is also presented in some details. Finally, a number of example problems are presented for a beam and plates rotating along a set of arbitrary axes, that testifies to the efficacy and broad applicability of the currently developed techniques. A comparison of CPU time is also provided for the current accelerated solution against the original simultaneous iterative method, noting the marked improvement. These techniques were incorporated in a multidisciplinary finite element analysis code [2], capable of solving a large array of practical problems.

ACKNOWLEDGMENTS

We wish to thank Dr. C. L. Lawson for his assistance in the implementation of the eigenproblem solution algorithm.

Thanks are due to S. Choi for his valued assistance in the preparation of this paper.

REFERENCES


