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INTRODUCTION

A computer program based on state-of-the-art compressor and structural technologies applied to bladed shrouded discs has been developed and made operational in NASTRAN Level 16.

The problems encompassed include aeroelastic analyses, modes and flutter.

The program is documented in the form of five NASA Contractor's Reports —— one Technical Report and four Updates to NASTRAN Level 16 Theoretical, User's, Programmer's and Demonstration manuals. This report describes the Theoretical manual updates.

THEORETICAL MANUAL UPDATES

18. AEROELASTIC, MODAL AND FLUTTER ANALYSES OF UNSTALLED AXIAL FLOW TURBOMACHINES

18.1 INTRODUCTION

The rotors and stators of axial flow compressors and turbines are subjected to centrifugal, thermal and airloads that depend on the geometry and the operating parameters. Steady aeroelastic and unsteady response of these "cyclically symmetric" structures, in turn, influence the applied thermal and airloads. These inter-active loads and responses arise fundamentally from the elasticity of the structure and determine the performance and stability characteristics of the "flexible" turbomachine.

Theoretical developments of References 1-3, have been applied to determine the thermal and airloads on the rotor/stator blade of an axial flow turbomachine. The computer code of Reference 1 has been adapted for NASTRAN in the functional module ALG to generate the steady state aerodynamic pressure and temperature loads. Computer codes of linearized, two-dimensional, harmonic cascade theories for subsonic and supersonic flows (References 2 and 3, respectively) have been utilized in the functional module AMG to estimate the harmonic airloads on the blade in a strip-theory manner. No transonic flow theory has been included presently, and the airloads on and near the transonic cylinder (or cone) are estimated by linear interpolation from subsonic and supersonic adjacent strip results.

These steady and harmonic aerodynamic theories, in conjunction with the existing structural analyses capabilities in NASTRAN have been implemented in the form of two new rigid formats to perform:

(1) Static aerothermoelastic "design/analysis", including differential stiffness effects, of an axial flow compressor rotor/stator (DISP Approach RF 16), and

(2) Cyclic modal, unstalled flutter and subcritical roots analyses of an axial flow compressor and turbine rotor/stator (AERØ Approach RF 9).

AEROELASTIC AND DYNAMIC ANALYSES OF TURBOMACHINES

The rigid formats are designed such that the rotor (or stator) of a single-stage, or of each stage of a multi-stage compressor or turbine is analyzed as an isolated structure.

Rigid formats have been designed in a modular fashion so that additional or improved aerodynamic computer codes could replace those currently incorporated.

18.2 STATIC AEROTHERMOELASTIC "DESIGN/ANALYSIS" OF AXIAL FLOW COMPRESSORS WITH DIFFERENTIAL STIFFNESS

At an operating point under steady-state conditions, the bladed-disc of the compressor is subjected to centrifugal, thermal and aerodynamic loads that result in deformation of the elastic structure. For a fixed flow rate and rotational speed, the deformation implies a change in the operating point pressure ratio.

The process of arriving at an "as manufactured" blade shape to produce a desired, design operating point pressure ratio at a given flow rate and speed is herein termed the "design" problem. The subsequent process of analyzing the performance of the "as manufactured" geometry at off-design conditions including the effects of flexibility is herein termed the "analysis" problem.

The current NASTRAN Static Analysis with Differential Stiffness rigid format has been modified to include the effects of non-aerodynamic (centrifugal, etc.) and aerodynamic (pressure and temperature) loads. The following remarks apply to the simplified problem flow and the algorithm shown in Figures 1 and 2, respectively.

1. The geometry of the compressor bladed-disc sector, its material properties and the applied constraints are used to generate and partition the elastic stiffness matrix. Non-aerodyanmic load vectors are formed and an operating point flow rate, speed, loss parameters, etc. are selected.

2. Based on the undeformed blade geometry and the operating point aerodynamic parameters, the functional module ALG generates the aerodynamic load vector.

3. Total loads are defined as a combination of aerodynamic and non-aerodynamic loads.

4. A linear solution for independent displacements is obtained based on the elastic stiffness and the total loads.

5. Omitted and constrained displacements are recovered, and stresses, reactions, etc., are obtained.

6. A differential stiffness matrix is derived as a function of the grid point displacements.

7. A total stiffness matrix is now defined as a sum (or difference) of the elastic and geometric (differential) stiffness matrices for the "analysis" (or "design") problem.

8. The linear displacements obtained earlier are used to revise the blade geometry and a revised aerodynamic load vector is obtained.

9. Again, the aerodynamic and non-aerodynamic load vectors are combined to define the total load vector.

10. A non-linear solution for independent displacements is obtained based on the total stiffness and the total loads.

11. Dependent displacements are obtained and data such as stresses, reactions, etc., are recovered.

12. Convergence of the solution is based on the parameter ε defined by

$$\varepsilon = \left| \frac{\lfloor u_g^b \rfloor \{P_{g12} - P_{g2}\}}{\lfloor u_g^b \rfloor \{P_{g2}\}} \right| \leq \varepsilon_0$$

Upon convergence, the final displacements, loads, the deformed blade geometry, etc., are output. Otherwise, further iterations are performed.

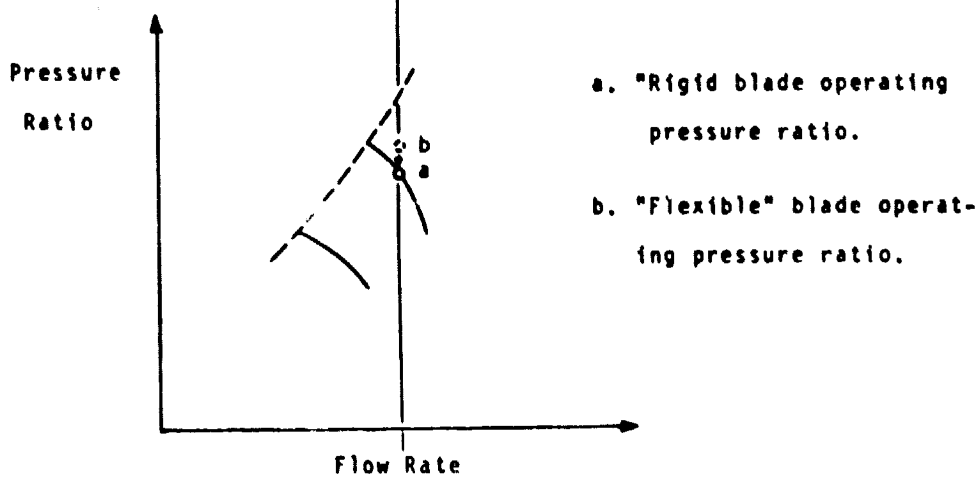
A decision to update the differential stiffness matrix requires a shift to the outer loop. Only the load vector is revised in the inner loop iterations.

12.1 The final pass, upon convergence, through the functional module ALG yields the "flexible" operating point pressure ratio (among other aerodynamic data), which can be relocated on the compressor map.

AEROELASTIC ANALYSIS OF TURBOMACHINES

The "design" mode of the rigid format is exercised only at the design operating point of the compressor. It is a two-step procedure in that having "designed" the blade shape, i.e., the "as manufactured" shape, it should be "analyzed" at the same operating point to confirm the design point pressure ratio. The "analysis" mode of the rigid format is a one-step procedure. The "designed" blade is "analyzed" at selected operating points over the compressor map, one at a time, to generate the "flexible" performance characteristics of the compressor. The differential stiffness matrix generated during the analysis can be saved for use in subsequent modal analysis.

1. Compressor bladed-disc sector geometry, constraints, stiffness matrix, non-aerodynamic loads + operating point (flow rate, speed, loss parameters, etc.).



2. Aerodynamic pressure and temperature loads, $\{P_g^A\}$ on undeformed blade, ALG

3. Total loads $\{P_g\}$ (Aerodynamic and non-aerodynamic)

4. Independent displacements $\{u_\ell\}$ (linear solution)

5. Dependent displacements, stresses, etc. (linear solution) → (A)

Figure 1. Simplified Problem Flow for Static Aerothermoelastic "Design/Analysis" Rigid Format for Axial Flow Compressors including Differential Stiffness Effects. (continued)

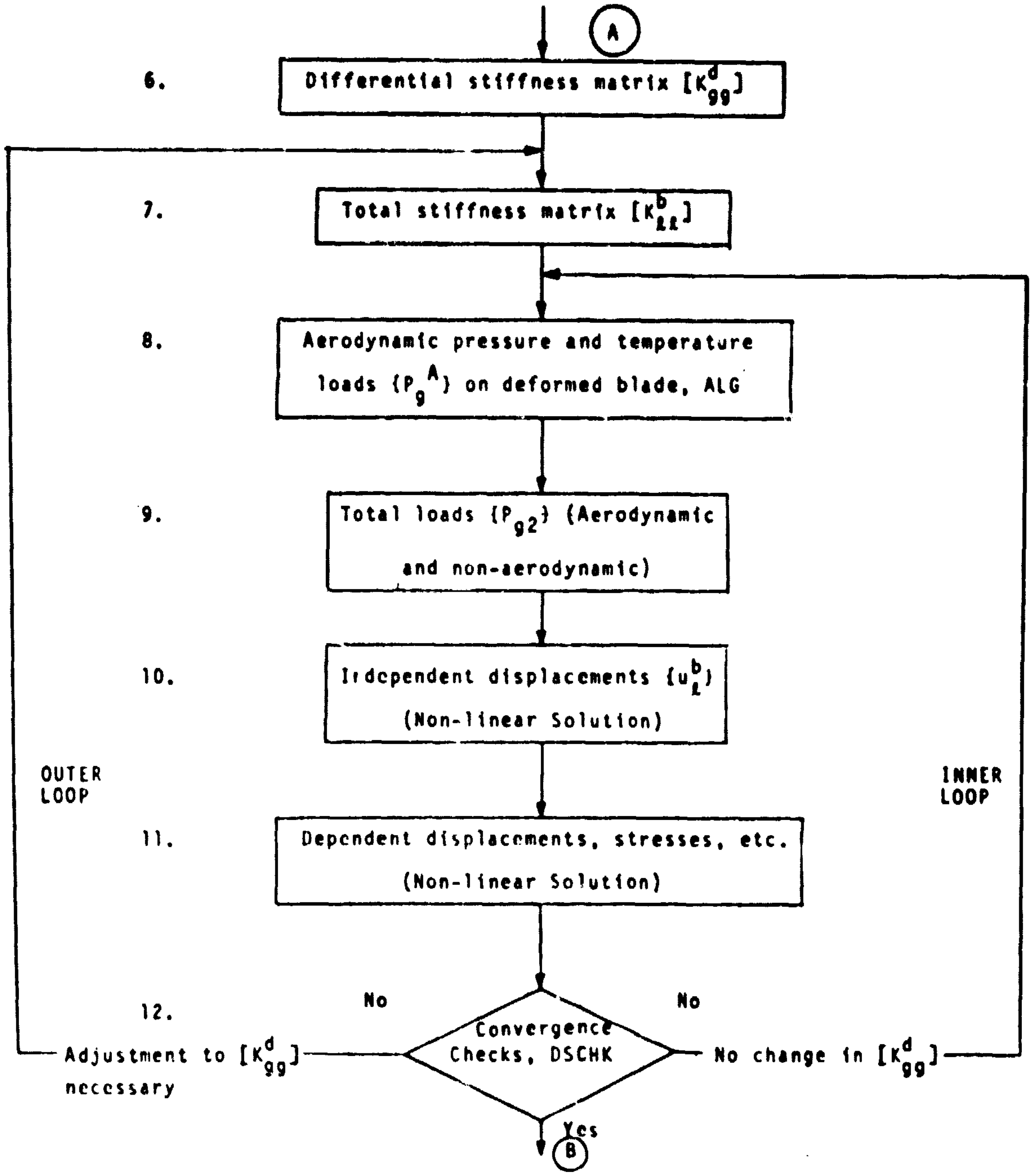


Figure 1. Simplified Problem Flow for Static Aerothermoelastic "Design/Analysis" Rigid Format for Axial FlowCompressors including Differential Stiffness Effects. (continued)

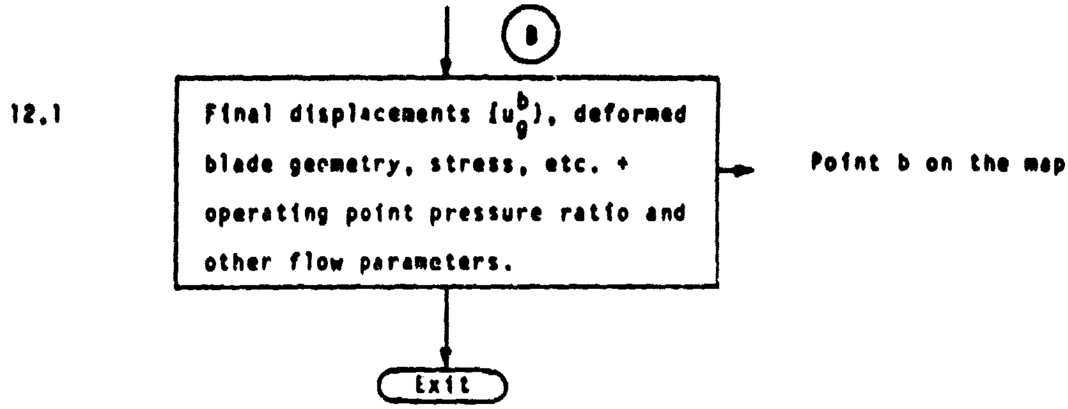


Figure 1. Simplified Problem Flow for Static Aerothermoelastic "Design/Analysis" Rigid Format for Axial Flow Compressors including Differential Stiffness Effects. (concluded)

1. Enter, after the application of constraints and partitioning to the stiffness matrix and the generation and transformation of the non-aerodynamic load vectors (centrifugal, etc.), with K_{aa}, P_g^{NA}, G_m, G_o, etc.

2. $\{P_g^A\} \leftarrow$ (ALG) $\longleftarrow$ Undeformed blade geometry + operating point (flow rate, speed, loss parameters, etc.)

   Aerodynamic Load Generator (pressure and temperature)

3. $\{P_g\} = \{P_g^{NA}\} + \{P_g^A\}$

   $\{P_\ell\} \xleftarrow[\text{partition}]{\text{constrain}} \{P_g\}$

4. $\{u_\ell\} = [K_{aa}]^{-1} \{P_\ell\}$

5. $\{u_g\} \xleftarrow[{[G_m],\ [G_o],\ \text{etc.}}]{\text{recover}} \{u_\ell\}$

6. $[K_{gg}^d] \xleftarrow{\text{generate}} [K_{gg}^d(\{u_g\})]$

   $\{P_g\} = \{P_g^{NA}\}$

   $\{P_{g1}\} = \{P_g\}$ - - - - - - - (A) OUTER LOOP begins

   $[K_{aa}^d] \xleftarrow[\text{partition}]{\text{constrain}} [K_{gg}^d]$

7. $[K_{\ell\ell}^b] = [K_{aa}] \pm [K_{aa}^d]$, (+) for "analysis" mode of the rigid format

   (-) for "design" mode of the rigid format

   $\{P_{go}\} = \{P_{g1}\} + \{o\}$

   $\{u_g^A\} = \{u_g\}$

Figure 2. Simplified Solution Algorithm for Static Aerothermoelastic "Design/Analysis" Rigid Format for Axial Flow Compressors including Differential Stiffness Effects. (continued)

- - - - - - - - - (B) Inner Loop begins

8. $\{P_g^A\} \leftarrow$ (ALG) $\leftarrow$ Deformed blade geometry, revised with $\{u_g^A\}$, + operating point.

9. $\{P_{g2}\} = \{P_{g1}\} + \{P_g^A\}$

$\{P_\ell^b\} \xleftarrow[\text{partition}]{\text{constrain}} \{P_{g2}\}$

10. $\{u_\ell^b\} = [K_{\ell\ell}^b]^{-1} \ \{P_\ell^b\}$

11. $\{u_g^b\} \xleftarrow[{[G_m],\ [G_o],\ \text{etc.}}]{\text{recover}} \{u_\ell^b\}$

$\{u_g^A\} = \{u_g^b\}$

$\{u_g^d\} = \{u_g\} - \{u_g^b\}$

$[\delta K_{gg}^d] \xleftarrow{\text{generate}} [\delta K_{gg}^d\ (\{u_g^d\})]$

$\{P_{gI1}\} = [\delta K_{gg}^d]\ \{u_g^b\} + \{P_{go}\}$

$\{P_{gI2}\} = \{P_{gI1}\} + \{P_g^A\}$

12. Convergence checks $\leftarrow$ (DSCHK) $\leftarrow$ $\{P_{g2}\}$, $\{P_{gI2}\}$, $\{u_g^b\}$

Differential Stiffness Checks

1. $\epsilon \leq \epsilon_o$.

Exit with

a. $\{u_g^b\}$, stresses, etc.

Figure 2. Simplified Solution Algorithm for Static Aerothermoelastic "Design/Analysis" Rigid Format for Axial Flow Compressors including Differential Stiffness Effects. (continued)

b. Final deformed blade geometry → (ALG) → $\{P_g^A\}$ + operating + operating point (flow rate, speed, loss parameters, etc.). <u>pressure ratio</u> and other flow parameters.

<u>OR</u> 2. $\varepsilon > \varepsilon_0$ <u>and</u> adjustment to K_{gg}^d <u>not</u> necessary.

Shift to the beginning of Inner Loop with

a. $\{P_{gl}\} = \{P_{gll}\}$ ---------------- (To B)

<u>OR</u> 3. $\varepsilon > \varepsilon_0$ <u>and</u> adjustment to K_{gg}^d necessary.

Shift to the beginning of Outer Loop with

a. $\{u_g\} = \{u_g^b\}$

b. $[K_{gg}^d] = [K_{gg}^d] - [\delta K_{gg}^d]$ ---------------- (To A)

Figure 2. Simplified Solution Algorithm for Static Aerothermoelastic "Design/Analysis" Rigid Format for Axial Flow Compressors including Differential Stiffness Effects. (concluded)

THEORETICAL MANUAL UPDATES

18.3 CYCLIC MODAL AND FLUTTER ANALYSES OF AXIAL FLOW TURBOMACHINES

The problem of determining the complete, unstalled flutter boundaries of a cyclically symmetric compressor or turbine bladed disc involves each member set of the series of harmonic families of its modes, and the effects of permissible interblade phase angle, over an adequate set of operating points (flow rates, speeds, pressure ratios, implied Mach numbers, etc.) of the performance map. In view of the large number of variables influencing the definition of the flutter boundaries, a thorough parametric study requires systematic effective solution procedure.

A capability, therefore, has been introduced in NASTRAN which, with repeated exercises over the range of variables involved, will enable determination of the flutter boundaries. The existing features of NASTRAN for Normal Modes Analysis using Cyclic Symmetry (Section 3.16, User's Manual) and Modal Flutter Analysis (Section 3.20, User's Manual) have been suitably combined for the cyclic modal, flutter and subcritical roots analyses in a new Rigid Format 9, Approach AERØ. Provision is also made to include the differential stiffness effects by using the total stiffness matrix saved from the Static Aero-thermoelastic Analysis (see Section 18.2).

In a compressor or turbine, an operating point implies an equilibrium of flow properties such as density, velocity, Mach number, flow angle, etc., that vary across the blade span. Blade properties such as the blade angle, stagger angle, chord, etc., also, in general, change from the blade root to the tip. The resulting spanwise variation in the local reduced frequency and the relative Mach number must be accounted for in estimating the chordwise generalized aerodynamic forces per unit span at each streamline. Integration of these forces over the blade span yields the blade generalized aerodynamic force matrix. Since the relative Mach number varies along the blade span, two two-dimensional, linearized, harmonic cascade theories (Refs. 2 and 3) one each for subsonic and supersonic flow have been implemented in a strip theory manner along the blade span. The chordwise aerodynamic matrices for streamlines with transonic inflow are derived by linear interpolation between those on adjacent (subsonic and supersonic) streamlines.

The generation of the generalized air force matrices is an expensive operation and should be judiciously controlled. In the present development, the aerodynamic matrices are computed at a few reduced frequencies and interblade phase angles, and interpolated for others. Additionally, the chordwise generalized air force matrices are first computed for "aerodynamic modes" (heave, pitch, etc.). The matrices for chordwise structural modes are then determined from bilinear transformations along each streamline prior to the spanwise integration to obtain the complete blade generalized aerodynamic matrix. This permits a change in the structural mode shapes of the same or a different harmonic number to be included in the flutter analysis without having to recompute the modal aerodynamic matrices for aerodynamic modes.

The following remarks apply to the simplified problem flow shown in Figure 1. In this figure, a compressor bladed disc performance map is shown, although the analysis is equally applicable to both compressors and turbines.

1. The geometry and the material properties of the bladed disc sector are defined along with the applicable constraints. An operating point is selected near the expected location of the flutter boundary. The solution procedure examines if this operating point is a flutter point.

2. Flutter parameters such as densities, interblade phase angles and reduced frequencies are selected.

3. The chosen operating point implies a certain spanwise variation of blade and flow properties.

4. A harmonic number is selected for the cyclic modal analysis. Grid point mass and stiffness matrices are generated. The stiffness matrix saved from a previous Static Aerothermoelastic Analysis can be used instead, and would include the differential stiffness effects at the steady state operating point under consideration.

5. Constraints and partitioning yield the analysis set mass and stiffness matrices.

6. Forward cyclic transformation results in the solution set mass and stiffness matrices for the cyclic eigenvalue problem.

7. Eigenvalues and eigenvectors in the solution set are obtained.

8. Symmetric components eigenvectors are derived by a backward cyclic transformation.

9. Symmetric components eigenvectors are augmented by recovering the dependent components, and are prepared for output if desired.

10. For a non-zero harmonic number, the symmetric component eigenvectors are partitioned to separate the cosine and sine components.

11. Based on the number of modes selected for flutter analysis the modal mass matrix is computed.

12,13. Direct input mass, stiffness and damping matrices, if necessary, and the constraints thereon define these matrices for further analysis.

14. The augmented eigenvectors, including any extra (or scalar) points introduced for dynamic analysis, are formed and used to define the new generalized mass, stiffness and

damping matrices.

15. The streamline generalized aerodynamic matrices for chordwise aerodynamic modes are generated. The variation of the relative Mach number from streamline to streamline dictates the use of either of the subsonic and supersonic harmonic cascade theories. Such matrices for the streamlines with transonic inflow are interpolated. No transonic flow theory has been currently included.

16. The structural modes are introduced via bilinear transformations along each streamline to define the chordwise generalized air force matrices.

17. The blade generalized aerodynamic matrix is derived by a spanwise integration of the chordwise aerodynamic matrices for structural modes.

18 - 20. The analysis loops through the user-selected combinations of density, interblade phase angle and reduced frequency.

21. Based on the (σ,k) combination, the appropriate blade aerodynamic matrix is chosen for the flutter equation. Linear or surface interpolation, at user's tion, is used if necessary.

22. The generalized mass, stiffness and damping matrices of Step 14 and the generalized air force matrix of Step 21 are used to define the modal flutter equations.

23. The solution to the flutter equations is sought in the form of complex eigenvalues and eigenvectors.

24. The velocity-damping and velocity-frequency curves output for each (ρ,σ,k) group are interpreted to identify flutter points.

25. Based on the relative stiffnesses of the blade and the hub of the bladed disc sector, a series of harmonic numbers are investigated before arriving at the flutter boundaries. Presently, the solution rigid format is designed to accept one harmonic number at a time.

The cyclic modal flutter analysis discussed herein is illustrated by the example 9-5-1 of the Demonstration Problems Manual.

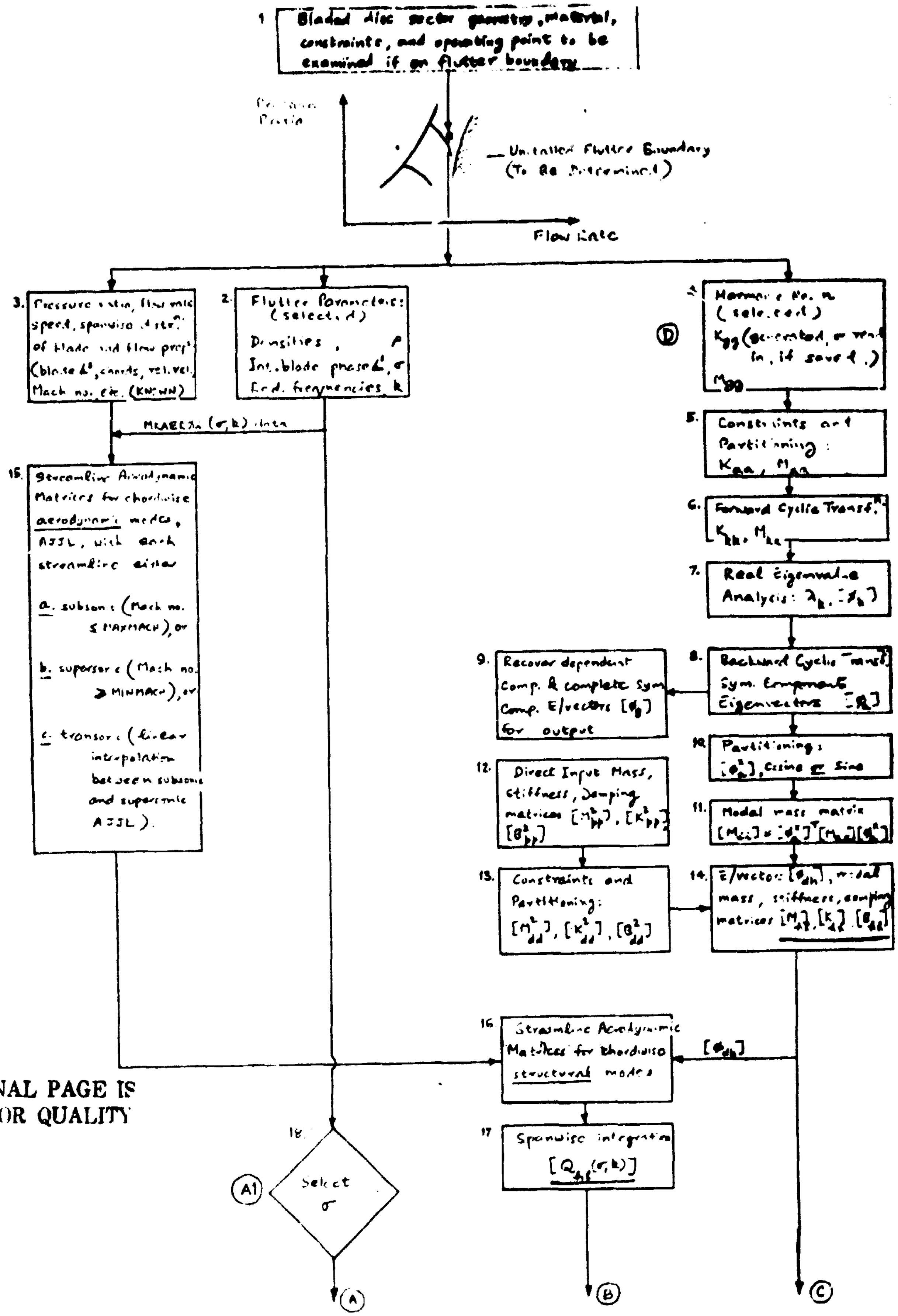


Figure 1 - ... Cyclic Modal Flutter Analysis of Bladed Discs (continued)

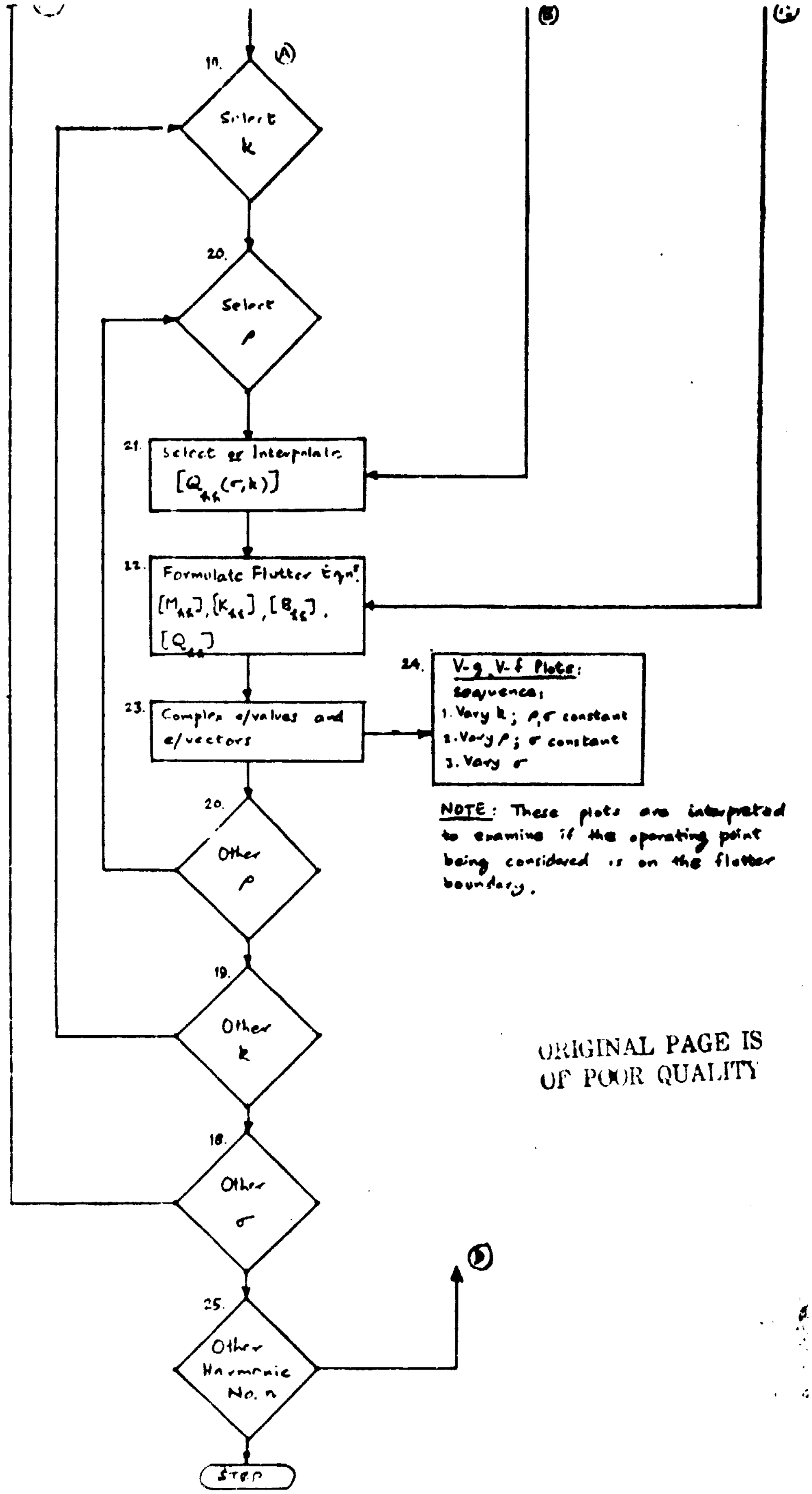


Figure 1. Simplified System Flow Cycle Modal Flutter Analysis of Bladed Discs (concluded).

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