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Finite element computational dynamics of rotating systems, an addendum (A bibliography (1998–2004))

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Gives a bibliographical review of the finite element analyses of rotating systems from the theoretical as well as practical points of view. The bibliography lists references to papers, conference proceedings and theses/dissertations that were published between 1998–2004. It is a continuation of the author's earlier bibliography with the same title published in *Shock Vibration* 6 (1999) 209–222 where papers published between 1994-1998 are listed. At the end of this paper 479 references are listed.

Keywords: Finite elements, rotor dynamics, shafts, blades, bibliography

1. Introduction

The output of scientific papers in general is fast growing and professionals are no longer able to be fully up-to-date with all the relevant information. The increasing specialization in various engineering fields has resulted in the proliferation of subject-oriented journals and conference proceedings directed to specialist audiences. The researchers have more channels for communicating the results of their research at their disposal, but on the other side to find necessary information may be a time-consuming and uneasy process. Another question is whether researchers/scientists are willing to spend time looking for information. It has been pointed out that in engineering, informal knowledge channels are the most frequently used means of obtaining information. Many professionals prefer to rely on personal judgment or on the wisdom of their colleagues whenever they have problems to solve.

In the last almost four decades the finite element method, FEM, has become the prevalent technique used for analyzing physical phenomena in the field of structural, solid, and fluid mechanics as well as for the solution of field problems. Modern rotating systems, often operating under extreme conditions and performing demanding tasks, are a prime machinery for transporting momentum, mass, and heat in many engineering systems. To understand the dynamics of these systems is very important in the design process as well as in the requirements to enhance the reliability and operational efficiency of these machines. In the design stage it is necessary to predict the dynamic behavior of rotor systems in bending and torsion, today frequently computed by using finite element techniques. This is the main subject of this bibliography. Topics dealing with fracture mechanics, fatigue, contact and stability problems of rotating machinery are also considered in separate sections.

It is difficult for a single author to summarize the wide topic of this paper in a form of the state-of-the-art review paper; therefore a pure bibliography is presented here. Hopefully, this bibliography will save time for readers looking for information dealing with subjects described below, not having an access to large databases or willingness to spend time with uncertain information retrieval.

This bibliography provides a list of references on finite element dynamic analysis of rotating systems and their elements. General solution techniques as well as problem-specific applications are

included. The emphasis is to present papers published first-of-all in journals. This type of papers is relatively easy to obtain. Conferences play an important role in scientific and technological communication by bringing together scientists, researchers and engineers, permitting informal exchange of ideas and information, and building up a network of personal contacts. The main criticism of conferences is that the material presented is often a repetition of what is published elsewhere in the literature. Also the complaint of uneven quality of papers is often heard. Conference papers are also a source of never-ending bibliographical confusion.

The entries of this bibliography have been retrieved from the author's database, MAKEBASE [1] and are grouped into the following sections and subsections:

- Rotors and their elements, rotors, discs, shafts, spindles, blades
- Fracture mechanics and fatigue
- Contact and contact-impact problems
- Stability analysis
- Specific industrial applications

Not included in the bibliography: drilling shafts, bearings, seals, passive/active vibration control, and optimization problems. References on passive/active vibration control can be found in [2, 3]. [4–11] are some books dealing with rotor dynamics, theory and practical aspects. Readers interested in the finite element literature in general are referred to author's Internet Finite Element Book Bibliography (http://www.solid.ikp.liu.se/fe/index.html), where approximately 500 book titles are listed and completed with bibliographical data, abstracts and contents.

2. Rotors and their elements

The basic elements of a rotor are the disc, the shaft, the bearings and the seals. In this section of the bibliography listed papers are dealing with dynamic finite element analyses of rotors and their elements, with emphasis on their characteristics and behavior. Free and forced vibrations are studied. A rotating shaft is typically modelled as a series of line or beam elements; papers on rotating beams are also included. The determination of natural frequencies and mode shapes of rotating structures, such as turbine blades is very important in the design of turbomachines. Therefore as special subsections also blades and spindles are addressed. The following subsections are included: rotors, discs, shafts, spindles, and blades.

2.1. Rotors

Topics included: linear and nonlinear finite element analysis of rotating machinery; multi-body dynamic modelling; modal analysis; transient analysis; free bending vibration analysis; linear and nonlinear vibration analysis; rotor impact studies; seismic response of rotating systems; vibration reduction in rotorcraft; propulsion vibration analysis; forward and backward whirling; bending deformation analysis; coupled bending torsional vibrations; effect of misalignment on rotor vibrations.

Types of rotor systems under consideration: multi-body rotors; multi-step rotors; composite rotors; flywheel rotors; actively twisted rotors; rotor-stator systems; rotor-bearing systems; rotor-bearing-foundation systems; rotor-fluid film bearing systems.

2.2. Discs

This subsection contains the following topics: free vibration analysis; dynamic response analysis; vibration and stability analysis; forced response analysis; friction induced vibrations; dynamics of

prestressed rotating discs; passive damping of spinning discs; reduction techniques for mistuned bladed discs.

Types of discs analysed: rotating isotropic/orthotropic/anisotropic discs; composite discs; laminated annular discs; functionally graded discs; bladed discs; bladed discs assemblies with friction dampers; roll-tensioned discs; disc-hat structures; bladed disc assemblies with shrouds; mock bladed discs; disc-spindle systems; mistuned bladed discs.

2.3. Shafts

The following subjects are considered: dynamic modelling of rotating beams/shafts; linear and nonlinear vibration analysis; coupling rigid and flexible body dynamics of rotating shafts; dynamic behavior of shafts; rotating shafts with large amplitude motion; forced large motions of spinning shafts; stiffness identification; torsion analysis of shafts; finite elements for shaft modelling.

Rotating systems handled: flexible shafts; composite shafts; D-shaped shafts; rotating Timoshenko beams; filleted shafts; slotted shafts; torque transmitting shafts; high-speed rotating shafts; rotor shaft rolling bearings systems.

2.4. Spindles

Topics included: dynamic modelling of spindles; vibration and deformation analysis; damping characteristics of spindles.

Rotating elements/systems: spindles; high speed air spindles; high speed spindle assembly; disc-spindle systems; machine tool spindle-bearing systems; aerostatic spindle-bearing systems.

2.5. Blades

This last subsection includes topics such as: dynamic modelling of rotating blades; modal analysis; linear and nonlinear vibration analysis; mode localization; forced response analysis; random vibration analysis; studies of flexure-torsion effects; external and internal damping; long blade vibration analysis; aeroelastic analysis; flutter of rotor blades; passive vibration suppression.

Components included: blades; composite blades; composite blades with multi-cell sections; blades with flexible coupling; bladed disc assemblies; frictionally constrained blade systems; propeller blades; turbine blades; rotor blades in hover; tuned and mistuned systems.

3. Fracture mechanics and fatigue

Rotating machinery components are prone to cracking and failure caused by creep, fatigue and their interaction. Fatigue crack studies are central to damage-tolerance approaches. Mathematical models of cracked rotor systems have been developed to predict the change in vibrational behavior due to crack growth. The main subject of this section are finite element, linear and nonlinear, studies of various aspects of vibration of rotating machinery with a crack.

Included are topics such as: 2D and 3D linear and nonlinear analysis of crack growth, crack initiation and crack propagation; crack growth from holes; creep crack problems; thermal cracking; low and high cycle fatigue; fretting fatigue; damage; fatigue life prediction; stress intensity factor studies; dynamic failure of rotating machinery; crack detection; probabilistic analysis.

The following cracked components are under consideration: rotors, shafts, discs, blades; turbopump blades; turbine blades, discs and rotors; helicopter rotor blades; fan blades; disc brakes.

4. Contact and contact-impact problems

The contact in rotating systems has long been recognized as a major contributor to their failures. Developing adequate contact models and incorporating them into the dynamic finite element analysis of rotating machinery are key issues in order to understand the mechanisms and in this way to predict accurately the phenomena. Many rotors also contain components stacked and held together. When the rotor whirls, working joints are causing the friction damping which is a potential source of instability.

Types of contact and contact-impact problems that are analysed/simulated in this section are, for example: unilateral contact applications to rotors; discs and multiple discs in contact; contact analysis of impact problems; contact on a disc brake rotors; contact analysis of drum brakes; head-disc interface contact mechanics; interaction between rotor-foundation systems; interaction between rotor-bearing-foundation systems; flexible supports and casings of rotating machinery; bonded attachments for rotors; joining problems; fretting of dissimilar contacting materials; sliding wear problems.

5. Stability analysis

Rotors should not be working in the unstable regime. The instability is included by fluid-solid interaction and can be seen as a spontaneous growth in whirl amplitude upon reaching some threshold speed. The sources of instability are bearings and seals, passive forces in turbines or impellers, internal friction, etc.

Vibration and dynamic stability/instability problems are the subjects of this section. The finite element method has been used for the following topics and components/systems: stability problems of rotating machinery; dynamic stability of bearing-rotor systems; aeroelastic stability; thermoelastic instability problems; imbalance response; stability loss analysis; stability analysis of rotors, shafts and blades; disc brakes; clutches and brakes; rotor blades; turbine blades; wind turbine blades; fan assembly.

6. Specific industrial applications

This last section includes the specific industrial applications of finite element analyses and design considerations of: turbomachinery rotors, discs and blades; wind turbine rotors and blades; helicopter rotors and blades; compressors; cam engine shafting systems; rotor dynamics in military vehicles; aerospace systems; disc drives; geared systems; mill spindles.

Acknowledgment

The bibliography presented in the Appendix is by no means complete but it gives a comprehensive representation of different finite element applications on the subjects. The author wishes to apologize for the unintentional exclusions of missing references and would appreciate receiving comments and pointers to other relevant literature for a future update.

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Appendix

This bibliography provides a list of literature references on finite element analyses of rotating machinery, theory and applications. The listing presented contains papers published in scientific journals, conference proceedings, and theses/dissertations retrospectively to 1998. References have been retrieved from the author's database, MAKEBASE. Entries are grouped into the same sections described in the first part of this paper, and sorted alphabetically according to the first author's name. In some cases, if a specific paper is relevant to several subject categories, the same reference can be listed under the respective section headings, but the interested reader is expected to consider also areas adjacent to his/her central area of research interest.

Rotors and their elements

Rotors

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