The use of higher order beam element based on the absolute nodal coordinate formulation in dynamic analysis of rotating shafts

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High-speed electric motors combined with modern enhanced control technology offer good efficiencies, excellent controllability, and reduced drive system complexity for many industrial applications. High-RPM motors can be the ideal solution for many pumps, compressors, generators and machine tool systems. However, there are numerous challenging areas of dynamics associated with the design of high-speed rotating systems, each subject to specific governing physical phenomena. Therefore, linear theory may not be acceptably accurate to simulate complex behavior under abnormal conditions or a machine system containing geometric non-idealities. Examples include the consequences of an electrical short circuit and a sudden imbalance due to a mechanical failure in a rotating component (such as impeller blade loss). In addition, high-speed rotating machines are subjected to cross section distortion such as radial expansion, which is proportional to speed of rotation. Significant cross section deformation mostly occurs in tubular shafts and results in gyroscopic and centrifugal stiffening effects. This successively influences the stability of shaft [1] .

In this study, a finite elements method based on the absolute nodal coordinate formulation (ANCF) is applied on the dynamic analysis of high-speed rotors. In the ANCF, elements are parameterized by slope vectors in transversal directions, which allows to describe shear and cross-sectional deformations [2]. To alleviate the various locking phenomena that may arise due to cross section deformation, several higher-order ANCF beam elements using the higher-order transversal derivatives have been introduced in previous studies [3, 4]. A four-node higher-order ANCF beam element with derivatives of order three in all directions is used in this study. The used element employs one position vector and nine slope vectors per node. The nodal location is depicted in Fig. 1. This study examines the above-mentioned four-node higher-order ANCF beam element by performing various benchmark tests associated with rotating structures. The employed element is capable of capturing complex cross section deformation modes more-accurately compared to lower-order ANCF beam formulations [5, 2].

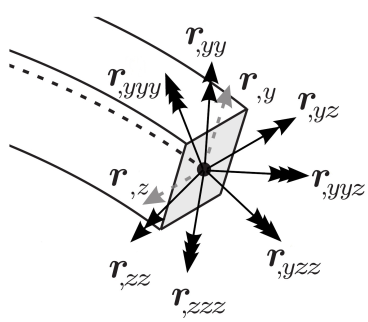

Fig. 1: Illustration of the employed ANCF beam element and its nodal degrees of freedom [4]

A number of static tests involving a beam with various boundary conditions and common cross section geometries subjected to pressure loads on the outer surfaces are analysed to verify the employed approach and also to show the versatility of the studied element. In the dynamic benchmark tests, a flexible rotating shaft is considered in order to investigate the performance of higher-order element in modeling the shaft cross section expansion (Δr) in high-speed operation. A solid element model constructed in the commercial finite element software ANSYS, comprising a significantly higher amount of degrees of freedom compared to the ANCF model, is used as a reference to verify the ANCF results, see Tab. 1.

Solution Approach	$\Delta r\ [\mu m]$
ANCF	7.3787
ANSYS	7.3688

Tab. 1: Comparison of the radial expansion of a rotating shaft with solid circular cross section, obtained by ANSYS and by higher-order ANCF beam element

Another example composed of a flexible hollow shaft with elliptical inner and circular outer surfaces is analysed using the higher order ANCF beam element to investigate the performance of the studied formulation when the unbalance due to varying thickness is taken into account.

According to the results, the employed beam element can capture more cross-section deformation modes, stress stiffening, and spin softening in the rotating shaft analysis.

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