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Cross-sectional constants of composite blades using computed tomography technique and finite element analysis

Sung Nam Jung [a,*], Manoj Kumar Dhadwal [a], Young Woo Kim [a], Ju Hyuk Kim [a], Johannes Riemenschneider [b]

[a] Department of Aerospace Information Engineering, Konkuk University, Seoul 143-701, Republic of Korea
[b] Institute of Composite Structures and Adaptive Systems, German Aerospace Center (DLR), Braunschweig, Germany

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ABSTRACT

The structural properties of Higher-harmonic Aeroacoustic Rotor Test (HART) II blades are determined using a finite element (FE) based cross-section analysis combined with the X-ray computed tomography technique. Three-dimensional, high-resolution digital images are constructed for this purpose. The detailed cross-section geometries are identified from a section segmentation process so that each pixel of the image is characterized by different attenuation coefficients according to the distribution of materials. The segmented section profiles are used to produce graphic data interfaces to create FE section model. A cross-section analysis is performed to compute the structural properties of the blade. The predicted mass and inertia results exactly reflect the manufactured configuration of the blade yielding semi-empirical data set of the blade. The stiffness properties measured using a cantilevered condition are correlated with the present predictions and the earlier estimated values. Good correlation is obtained between the predicted results and the measured data while a substantial deviation is observed with the earlier estimations. The possible source of discrepancy is identified from the analysis. The sensitivity of manufacturing defects and modeling deficiencies on the structural properties is examined. It is demonstrated that the proposed analysis offers a practical alternative for structural properties in non-destructive way.

1. Introduction

The wind tunnel test campaign of HART II rotor was conducted in 2001 in the open-jet anechoic test chamber of the German–Dutch facility (DNW) [1]. A massive amount of data on airloads, tip vortex trajectories, blade motions, noise levels, and structural moments of the rotor have been generated from the international joint research. The test data were released to the public in 2005, which motivated many researchers to validate their prediction tools and to figure out the detailed flow physics around a rotor in descending flight [2]. These studies led to a remarkable success in the rotorcraft aeromechanics fields and contributed significantly to advance the prediction capability. However, most of HART II validation conducted so far adopted the blade section properties estimated by MBB (Messerschmitt–Bölkow–Blohm) [3], the manufacturer of the HART II blades.

To determine the structural properties of a blade, especially in the post-manufacturing stage such as the case of HART II blades, a destructive type of testing is necessary taking into consideration the manufacturing tolerances and material uncertainties associated with the fabrication of the blade. The destructive testing includes chopping of the blade into several pieces to determine sectional mass and inertia properties. Jung and Lau [4], and Jung et al. [5] reported the measurement of the elastic properties of HART blades, the precursor of HART II blades. The three-point bending as well as an optical method based on mirrors glued on the blade surface were employed to evaluate the section stiffnesses while the inertia properties were obtained using the trifilar pendulum technique from the cut-out sections. The measured blade properties were compared with the earlier predictions obtained by the manufacturer of the blades (Dynamic Engineering, Inc.). Much improved correlations were reached in the rotor aeromechanics predictions when compared with the wind tunnel test data. More importantly, the uncertainties associated with the blade elastic properties were resolved significantly through the measurement process. Shekoski [6] conducted the measurement of TRAM

* Corresponding author.
E-mail addresses: snjung@konkuk.ac.kr (S.N. Jung), manojkd@konkuk.ac.kr (M.K. Dhadwal), johannes.riemenschneider@dlr.de (J. Riemenschneider).

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(Tilt Rotor Aeroacoustic Model) blade properties using the destructive testing. A production TRAM blade with a length of about 1160 mm was cut into 47 slices to identify the mass and inertia properties.

These conventional blade property tests inevitably brought the demolition of blades. Recently, with advances in computer and software technologies, the application of a non-destructive technique such as the X-ray computed tomography (CT) scheme became realized in the field of the helicopter aeromechanics. Schulz et al. [7] used the X-ray CT for the measurement of mass properties of STAR (Smart Twisting Active Rotor) blades [8]. A three-dimensional digital image reconstruction was carried out using a series of projected, two-dimensional radiographic images taken around a single axis of rotation [9]. The detailed interior structural layouts of a blade cross section were determined using the fact that each pixel (picture element) of the image has a CT number (or Hounsfield number) which varies with the physical density of the material in use. The section segmentation was then made to identify regions with the same material in the scanned image of a section. The mass properties obtained from the segmented image were verified comparing with the measured data. A good agreement was achieved with the CT scan technique. This newly established X-ray CT scan technique can be exploited to evaluate the structural properties of HART II blades where a destructive testing is prohibited.

Since the X-ray CT technique allows capturing the actual, post-manufactured geometries and surface boundaries of a blade section, it can be extended further to evaluate not only the mass and inertia properties but also the section stiffnesses and geometric offsets by combining this technique with a cross-section analysis. Jung et al. [10] covers an extensive survey of composite rotor blade modeling techniques encompassing thin- and thick-walled, classical and non-classical effects, non-uniformity, and inhomogeneity of composite beams. They later developed a mixed (displacement and stress) beam theory that can describe thin-walled composite blades with arbitrary geometries and material distributions [11]. In addition to the contour-based analytical beam approach, a finite-element (FE) cross-section analysis code called Ksec2d was developed to model and analyze composite blades with general topology sections [12,13]. Good correlations were obtained for various non-homogeneous beams with different section shapes as compared with analytical solutions or experimental data. The theoretical foundation was built based on a displacement formulation under the assumption of linear elasticity [14]. Other well-known and more rigorous cross-section analysis systems include VABS (Variational Asymptotic Beam Section Analysis) [15] and PreComp (Pre-processor for Computing Composite Blade Properties) [16] in the fields of helicopter and wind turbine rotor blades, respectively. It is noted that more advanced theory like VABS [15] is desired to analyze composite beams with non-vanishing elastic couplings. However, in cases with zero or negligible elastic couplings, any simple but generic beam section approach may lead to the same level of precision that can be reached by the most sophisticated beam section approach. Note that the material properties available for HART II blades are isotropic or at best quasi-isotropic resulting in zero elastic couplings which renders the analysis quite simple.

The present study aims at the evaluation of HART II blade structural properties using a FE based cross-section analysis combined with the X-ray CT scan technique. The previous cross-section analysis [12,13] is refined incorporating an anisotropic elasticity approach with the St. Venant beam assumption. The cross-section analysis is validated illustrating several benchmark examples, as compared with the closed-form solutions and other analysis results. The present study is fundamentally different from other conventional analytical approaches in that: (1) The detailed cross-section profiles of the final fabricated blades are determined directly from the high resolution X-ray CT scan images; (2) The manufacturing imperfections (e.g., air pockets and wriggles) and sensor installations are naturally taken into account in the modeling stage of the blade section analysis. The accuracy and reliability of the predicted section properties of HART II blades are evaluated as compared with the measured data and the earlier estimated values.

2. HART II blades

The HART II rotor tested in the German–Dutch wind tunnel (DNW) is presented in Fig. 1. The rotor is composed of four blades, rotating counterclockwise viewed from the top. The rotor is Mach-scaled to match the production BO-105 blade characteristic [17]. The rotor has solidity of 0.077 with radius (R) 2 m and chord (c) of 0.121 m. The model rotor is in descending flight with an advance ratio $\mu = 0.15$, hover tip Mach number $M = 0.6387$, and thrust level $C_T = 0.00457$. The detailed information on HART II rotor test can be found in the test documentation [17] and the HART II international workshop papers [2].

Fig. 2 shows a photograph taken recently for the HART II blades, each of which is used for the wind tunnel test campaign in 2001. As can be seen, the blades are identified with the color ribbons wrapped around the blade root region: yellow, green, blue, and red in the order that they are installed in the rotor system. One spare blade referred to as H2S (in mixed color ribbon) is set aside for redundancy. The No. 1 blade (yellow; not shown) is used as the reference and fully-instrumented with pressure sensors positioned at 87% radial station. The preceding No. 4 blade (red) is also equipped with a number of pressure sensors distributed along the span to investigate the turbulence and broadband noise signals [17]. For each blade, six strain gages are attached in the blade root region to evaluate the structural loads: three for flap, two for lead-lag, and one for torsion. Due to different sensor instrumentations, the weight is varied between the blades: 2.14 kg, 2.06 kg, 2.03 kg, and 2.10 kg for No. 1 to No. 4 blades, respectively. The blade H2S has the same structural layout and material composition as the other four blades, and is installed with dummy cables and aluminium tubes, leading to a weight of 1.96 kg. Note that, since all blades remain intact and clean and they shall be in use for further testing in the future, no destructive testing is allowed at the present moment. Therefore, non-destructive test schemes such as X-ray CT scan technique is adopted in this study. The blade H2S is used to scan the detailed interior layout and structure of the blade, and ultimately to determine the overall blade cross-section properties. It should be mentioned that the blade H2S is chosen for the X-ray scan operation due to the fact that H2S has no blade root

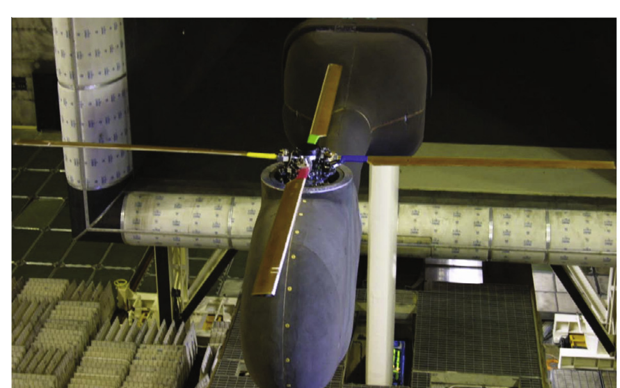

Fig. 1. HART II rotor in the German–Dutch wind tunnel (2001).