Photogrammetric detection technique for rotor blades structural characterization

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Abstract. This paper describes an innovative use of photogrammetric detection techniques to experimentally estimate structural/inertial properties of helicopter rotor blades. The identification algorithms for the evaluation of mass and flexural stiffness distributions are an extension of the ones proposed by Larsen, whereas the procedure for torsional properties determination (stiffness and shear center position) is based on the Euler-Prandtl beam theory. These algorithms rely on measurements performed through photogrammetric detection, which requires the collection of digital photos allowing the identification of 3D coordinates of labeled points (markers) on the structure through the correlation of 2D pictures. The displacements are evaluated by comparing the positions of markers in loaded and reference configuration. Being the applied loads known, the structural characteristics can be directly obtained from the measured displacements. The accuracy of the proposed identification algorithms has been firstly verified by comparison with numerical and experimental data, and then applied to the structural characterization of two main rotor blades, designed for ultra-light helicopter applications.

1. Introduction

The correct evaluation of the structural properties of existing rotor blades is an important and complex task. Indeed, quantities such as flexural and torsional stiffness and mass distribution are fundamental parameters in understanding, simulating and optimizing rotors [1, 2], in that they drive the aeromechanical/aeroelastic response of the whole helicopter [3, 4]. Similar considerations may be carried out for wind turbines, whose performance and stability may be strongly affected by these parameters [5].

Two main reasons make experimental testing a necessary approach in many cases: (i) data provided by manufacturer may be incomplete, approximated or, in the worst case, totally missing, (ii) the need to perform quality check in order to assess the compliance of the actual object with nominal design.

This paper presents the research and industrial activity carried out by Roma Tre University with I.R.I. Helicopters (www.irihelicopters.eu) and Globalsensing (www.globalsensing.it), aimed at defining main rotor blade structural characteristics of IRI T22/T23 helicopters. This
activity is initially addressed to assess the IRI T22/T23 aeromechanical/aeroelastic behavior, with the aim of a near-future optimal redesign of the main rotor to improve flight performance and comfort. Consequently, three main objectives have driven this work: (i) to develop non-invasive techniques for the structural characterization of slender beams (as rotor blades are), (ii) to assess their effectiveness and accuracy when used in real-world applications, and (iii) to use them for the structural characterization of the main rotor blades of the I.R.I. T22/T23 helicopters. The algorithms adopted for the prediction of structural/inertial properties are inspired to those presented in [6], and extended to evaluate blades torsional properties and to take into account the presence of concentrated masses. A key aspect in using such algorithms for blades structural characterization is the definition of appropriate experimental data collections (displacements and/or deformations), that are usually identified through dedicated bending and torsion static tests.

Typically, experimental campaigns make primarily use of strain gauges as measurement sensors to relate local strains, known applied loads and unknown structural properties [6]. Strain gauges (both traditional or Fiber-Bragg-Grating-based ones) have a significant marginal cost which makes them an expensive solution when several acquisition points are required. Moreover, they require careful positioning and gluing as well as complex wiring which may interfere with the structure to be characterized. In this work, a non-invasive measurement technology, based on photogrammetric detection [7, 8, 9], is proposed. This technique allows an accurate reconstruction of the shape of the object from a number of digital pictures taken freehand from different angles and positions. A triangulation process, based on the correlation of the digital pictures, yields 3D coordinates of designated reference points (markers) located on the structure [7]. Since photogrammetry basically consists in pasting adhesive markers and taking a set of 2D photos, it has several advantages in terms of reduced cost and intrusion, as well as in terms of easiness of setup and measurement.

The accuracy of the proposed technique has been firstly verified by numerical FEM simulations, and then through the experimental characterization of a certified aluminum C-shaped profile, whose properties were accurately defined and controlled. Finally, it has been applied to the definition of the structural/inertial properties of two different blades: the Robinson R22 aluminum blade [10], and the CFRP blade [11] that was specifically designed for application on IRI T22/T23 helicopters.

2. Methodologies
In this section a brief description of the photogrammetric detection technique is presented, as well as the theoretical aspects regarding the formulations proposed for the identification of stiffness and mass distributions.

2.1. Photogrammetry
Close-range photogrammetric detection [12] is an innovative, non-invasive measurement technique that allows an accurate reconstruction of the three-dimensional shape of an object from a number of freehand digital pictures taken from different angles and positions. The object is reconstructed through the knowledge of the positions of a set of circular and coded markers pasted on its surface, as described in the following. The object coordinates corresponding to the circular markers and the orientation of the camera are estimated simultaneously with a process called “bundle adjustment”. This task is performed by an algorithm that post-processes the data by simultaneously recognizing and triangulating the target points, resecting the pictures and self-calibrating the camera [12].

In general, in order to triangulate a 3D point, the orientation of the 2D pictures (at least two, according to basic stereoscopy principles) must be known; vice versa in order to determine the orientation of the camera, the coordinate of the points are needed. The commercial software
used in this study, TRITOP, performs these two actions together and does not require any additional information than 2D pictures; indeed it is able to reconstruct the camera locations of every picture and its accuracy is ISO 10360 certified.

This software imposes a series of collinearity conditions based on the hypothesis that a point in 3D space, its projection on a plane, and the projection center lie on the same line (see, figure 1). In modern cameras this is not strictly true, but a correction that depends on lens optics and sensors can be implemented. The technique is extremely simple to set up: several circular and coded markers (figure 2), and orientation crosses (figure 3) are pasted on the structure and its surroundings. The surrounding points are used to simplify the correlation process and lock in place a reference points system (RPS) valid for the whole session.

The circular and/or the coded markers must be placed in points of interest (figure 4), since they will be the ones whose location will be calculated. A calibration bar of known length is
required in order to correlate pixel to meters. The temperature of the bar can be included as a parameter in the software, in order to take into account thermal expansion.

The typical acquisition procedure contemplates taking photos from viewpoints located on three ideal circles around the structure at different heights (top view, in plane view, bottom view). In each picture, at least 5 coded markers must be present to let the program accurately compute camera locations. Having this number as a reference, the operator achieves the correct balance between too few visible markers (that can reduce the number of usable pictures) and too many points (that would slow down the post-process). An additional aspect to consider is that each coded marker has to be present in at least three different pictures, to accurately determine its position in space [12].

All collected images are then loaded in a computer and the digital model is automatically reconstructed (see figure 5) with an accuracy of 0.01 pixels (hundredths of a millimeter...
considering the camera used in this work and the dimension of the objects).

Note that, although the description above is focused on static measurements, the extension of such a technique to dynamic analyses can be easily achieved by making use of a couple of high-frequency cameras instead of a regular photographic camera.

2.2. Mathematical models
Starting from the fact that photogrammetric measurements yield the positions of marked points in a given frame of reference, displacements have to be obtained by difference between deformed and reference configurations. Such an approach has been applied in this work to identify the input data (i.e., body displacements and deformations) of the mathematical algorithms used to define the blade structural/inertial properties, which are based upon the Euler-Bernoulli beam model.

The identification procedure proposed in this work starts with the definition of the blade elastic axis. The basic idea behind the procedure is that by performing two (or more) experimental tests, with identical loads applied in different positions at the tip of a cantilever blade, there exists only a point for each cross section (shear center) that has the same displacement in all load conditions. The locus of these points defines the blade elastic axis.

![Figure 6: Schematization of the tip section displacements for the same load applied in two different positions.](image)

In figure 6 an explanatory application of the proposed procedure to a single (rigid) cross section is presented. In this example, the blade thickness is neglected and hence only the technique for the identification of the chordwise position of the shear center is shown. Under the hypothesis of small torsional deformations (i.e., small section rotation angle), displacements of the blade cross section points lie on straight lines, whose intersection defines the shear center location.

Under the Euler-Bernoulli beam theory hypotheses, for each load condition, the displacements \( v_i \) and \( w_i \) (respectively on \( y \) and \( z \) direction) of the \( i \)-th section point and the section rotation angle are related by the following equations

\[
\begin{align*}
v_i(x) &= v_E(x) - (z_i - z_E) \theta(x) \\
w_i(x) &= w_E(x) + (y_i - y_E) \theta(x)
\end{align*}
\] (1)

where the subscript \( E \) identifies the shear center. From the knowledge of the displacements of section markers, Eq. (1) can be solved through a least squares approach to estimate both shear center and section rotation angle.

1 For mathematical developments, a cartesian coordinate system is introduced, with the \( x \)-axis directed along the blade axis and the \( y \) and \( z \) axes lying on the blade cross-section plane.
The procedure used to define bending stiffness and mass distribution is an extension of that proposed by Larsen [6]. In particular, the bending stiffness is evaluated by considering unsymmetrical loading conditions. These are usual in aeronautical applications, in that they are present when structures are twisted or loads are applied along non-principal axes. Under this hypothesis, the equilibrium equations between internal stresses and external bending moment yield

\[
\frac{\partial^2 v_E}{\partial x^2} = \frac{I_{yz}(x)M_y(x)}{EI(x)} - \frac{I_{yz}(x)M_z(x)}{EI(x)}
\]

\[
\frac{\partial^2 w_E}{\partial x^2} = \frac{I_{yz}(x)M_z(x)}{EI(x)} - \frac{I_{yz}(x)M_y(x)}{EI(x)}
\]

Equations (2) are solved in terms of the three unknown quantities \((EI_{yy}, EI_{zz}, EI_{yz})\), by evaluating them for at least two different load conditions, and using a least square approach. Note that, to reduce the impact of measurement errors and scatter phenomena, a polynomial interpolation of the elastic axis displacements \((v_E, w_E)\) is suggested before performing the differentiation in Eq. (2).

Following Ref. [6], the distribution of mass per unit length along the blade radius, \(\rho\), is expressed as a linear combination of suitable functions whose coefficients are evaluated by minimizing

\[
U = \sum_{j=1}^{J} \left( \frac{\tilde{M}_j - M_j}{\sigma_j} \right)^2
\]

that is, the difference between the gravity bending moment, \(\tilde{M}_j\), experimentally measured at given points along the blade axis, and the corresponding values, \(M_j\), of the bending moment due to the unknown mass per unit length, \(\rho\)

\[
M_j = g \int_{x_j}^{x_j+L} (x - x_j) \rho(x) dx
\]

Note that, in Eq. (3) \(\sigma_j\) is the variance of measurement noise [6]. The novelty in the mass identification approach proposed here is the possibility of simulating concentrated masses (which are common in rotorcraft applications), by including the Dirac delta function among the interpolating functions. In this case, the general expression for \(\rho\) is given by

\[
\rho(x) = \sum_{i=1}^{N} \sum_{k=0}^{K} P_i^k(x)H_i + \sum_{l=0}^{L} b_l \delta(x - x_l)
\]

where \(N\) is the number of elements (portions) in which the blade has been divided, \(K\) is the maximum degree of the polynomial \(P_i^k(x)\), \(H_i\) is a rectangular window defined on the \(i\)-th blade portion, \(\delta(x)\) is the Dirac delta function at \(x_l\), and \(L\) defines the number of concentrated masses. Combing Eqs. (3) and (5), the minimization of the functional \(U\) with respect to the coefficients \(a_i^k\) and \(b_l\) is performed by using a quasi-Newton method [13]. Constraints on the position of blade center of gravity and blade total mass are easily included in the minimization process by using the Lagrange multipliers technique.
The mathematical model used to determine the distribution of torsional stiffness is again derived from the Euler-Bernoulli beam theory. In order to generate maximum torque for a given bending moment, the cantilevered blade is loaded with a weight, \( W \), located at tip as far as possible from the (estimated) shear center. The torque can be expressed as 

\[ T = rW \]

with \( r \) denoting the moment arm of the load \( W \) with respect to the shear center. Imposing torsional equilibrium of each blade cross section along the axis, the torsional stiffness distribution, \( G_J(x) \), is obtained as

\[ G_J(x) = \frac{T}{d\theta/dx} \]

where the torsion angle distribution, \( \theta(x) \), is evaluated through Eq. (1). Even in this case, a polynomial fit of the cross-section torsion angle along the blade span is suggested.

Finally, it is worth noting that the proposed algorithms for the evaluation of blade structural properties are rigorously valid only far enough from the constrained boundary (i.e., the root section in experimental results presented in the following), otherwise correction factors must be included in above equations (see, for more details Ref. [14]).

3. Numerical FEM verification

To assess the validity of the identification techniques described in the previous section, as well as to investigate the limits of applicability of the proposed algorithms, the experimental campaign was preceded by a simulation phase on test cases with increasing complexity, performed with a commercial FEM software. After every simulation, the displacements of a set of points were collected in order to simulate a photogrammetric measurement campaign. These data were then post-processed with the algorithms shown above. In the following, a narrowed selection of the obtained results is shown. In particular, results presented in figures 7-10 pertain a straight-axis cantilever beam with large variations in bending and torsional stiffnesses, with a concentrated mass near the tip.

As expected, the agreement between structural properties predicted by the proposed algorithms and the nominal ones is very good, except in the beam region nearby the clamped end, where boundary effects become not negligible (this is particularly evident in figures 7 and 10, where results regarding shear center location and torsional stiffness distribution are presented).
4. Experimental validation

Before performing the experimental campaign on helicopter blades, a certified (both geometrically and structurally) test beam has been analyzed. This step of the validation procedure is fundamental to assess the applicability/accuracy of the measurement technique to a real case study, in order to highlight possible criticalities that may arise. Note that, exploiting beam cross section (a 40x15x3mm C-shaped profile) symmetry, in this analysis $y$ and $z$ axes are made coincident with the cross section principal axes, with the consequence that the coupling stiffness $EI_{yz}$ is equal to zero (the only non zero stiffnesses are $EI_{yy}$ and $EI_{zz}$). The loads have been applied with a suitably designed saddle, shown in figure 11, and some markers were pasted on it, in order to determine the load application point.

Figure 11: Beam load saddle and weights.

Figure 12: Beam root section, with circular markers.

The beam was cantilevered by fixing 10 cm of the root region to a steel girder (carefully oriented according to a centesimal spirit level) with two screws and two steel strips. Then, circular and coded markers were applied on several sections of interest on the beam, as shown in figure 12. Eight cross sections were marked, with four circular markers each (two on top and one on each side). The photogrammetric measurement sessions were performed with a 21 Megapixel commercial-grade camera, equipped with a flash and wide-angle optics. For each measurement, about 40 photos were taken.

The identified beam characteristics are compared in figures 13 - 17 with the nominal values. In particular, figure 13 depicts results concerning the shear center identification. Also in this
case, the accuracy of the proposed procedure is confirmed, with the only exception of a small region nearby the beam clamped end, where some discrepancies appear.

For this application, the mass identification algorithm has been used without including constraints on total mass and center of mass location (otherwise, being the mass distribution uniform, the measurements would be unnecessary). The identified distribution seems to be in a satisfactory agreement with the mass nominal value (see, figure 14), with an identification error of about 7%.

For what concerns flexural stiffness, the initial identification showed a large error in the tip area (see, figure 15). This was due to the fact that the stiffness is defined as the ratio between bending moment and second order derivative of displacements, which become very small in this region yielding to an ill-conditioned expression. To solve this problem, a correction was included by forcing second order derivative of the displacement to zero at the load application point (note that the bending moment is exactly zero at this point). The new result is shown in figure 16 and it is in very good agreement with the nominal value (the average error is less than 1-2%).

Torsional stiffness identification provides satisfactory results, even if two experimental tests, performed by applying the same load at two blade tip chordwise locations, provided different
values for the shear modulus. However, in both cases the average error is acceptable, being less than 2% or 5%, respectively.

5. Experimental results on actual blades

Once the reliability of the technique were successfully confirmed with the aluminum beam test case, two main rotor blades have been investigated. The first one is a metallic R22 blade [10], whereas the second one is a carbon composite blade [11]. For the last blade, the plies orientation are such as to reduce the structural (bending/torsional) couplings, which will be then neglected in this study (i.e., the blade has been considered isotropic). Moreover, since thickness of blades cross sections is small compared to the chord, the coupling stiffness, $E I_{yz}$, is negligible with respect to the flapping and lagging ones.

The photogrammetric acquisition has been performed by placing seven circular markers per section on sixteen sections along the blades span. The blade root constraint and the load saddle, respectively shown in figures 18 and 19, were specifically designed for this test campaign. The load saddle modularity allows both flapwise and chordwise loading. In order to apply a significant twisting moment for a given bending moment, an extension bar has been fixed to the saddle, moving the load application point (identified by a marker) far apart from the supposed elastic axis position.

The photogrammetric acquisitions has been performed with the same camera described in section 4, and the number of pictures taken for each session was raised to 80-120, depending on the software needs. Several test sessions have been performed and the results shown in the following are obtained as average of the measurements of all tests made.

The identified blade properties are compared with the corresponding nominal values, where present. Note that nominal characteristics are estimated by the manufacturer as constant along the entire blade, and then are not expected to exactly match actual values, in that both blades present stiffened root regions.

Figures 20-21 show the predicted location of the elastic axis for the aluminum and composite blade, respectively. In both cases, the elastic axis is located, as expected, really near to the quarter-chord.

Next, figures 22-23 show the flapping stiffness predicted for the two blades. In both cases, the bending stiffness presents two specific areas: the root area (up to about 75cm) where high values and a steep variation can be appreciated, and an external area where the stiffness is uniformly
distributed along the span (in accordance with the manufacturer specifications). Note that, since displacements are very small in the inner part of the blade (root region), the proposed procedure may suffer from loss of accuracy. The application limited to the blade root region of strain-based measurements could help to improve the predictions, since strains are maximum there.

Similarly, figures 24-25 show the predicted lag stiffness, for which a constant distribution is expected to be a good approximation. The predicted lag and flap stiffnesses have been used in the analytical formula for the evaluation of tip deflection of a cantilever beam with loaded end, producing a displacement value very close to that measured in the test campaign. This suggests that the nominal stiffness value stated by the manufacturer is probably an average value along the entire blade span.

The identified torsional stiffnesses (supposed to be uniformly distributed along the blade) for the R22 and composite blades are 3260 $Nm^2$ and 2735 $Nm^2$ (comparable to those of similar-class helicopter blades), respectively. Moreover, even in this case, analytical static tip torsion deflection is comparable with that measured in the experiment.

Finally, the mass distribution, shown in figures 26-27, has been identified by dividing the blade in two portions and assuming a linear behavior in each of them. Moreover, a concentrated mass near the tip has been hypothesized, and both constraints on total mass and center of mass position have been imposed. Note that the values of the estimated concentrated mass is 1.5
times higher (for the metallic blade) or lower (for the composite one) than the expected ones (which are declared by manufacturer to be about 5% of total blade mass), suggesting that the
Table 1: Relative error on measured and predicted blade eigenfrequencies.

| Mode  | Relative error |
|-------|----------------|
| 1st Flap | < 0.5% |
| 1st Lag  | < 0.5% |
| 2nd Flap | 6.6%  |
| 3rd Flap | 6.8%  |

The proposed algorithm is very sensitive to measurement errors and beam model inaccuracy.

However, to further assess the accuracy of the identified structural and mass distributions, the non-rotating blade eigenfrequencies predicted by the blade structural solver presented in [2] have been compared with those experimentally observed. Even though the presentation of this experimental campaign is well beyond the aims of this work, results for the R22 blade are summarized in table 1 for the sake of completeness (note that torsional frequencies are not included, since the proposed identification technique it is not able to provide sectional moment of inertia). These results seem to further confirm the overall quality of the identified quantities.

6. Conclusions

In this paper, an innovative photogrammetric detection technique has been applied to structural characterization of beam-like structures. This technique presents some advantages with respect to strain gauge measurements, related to the low cost and easiness of installation, as well as to its characteristic of being a non-invasive measurement technique.

A structural/inertial characterization procedure has been introduced and tested with numerical and experimental tests on an aluminum beam, and has been used for the structural characterization of the main rotor blades of the ultra-light IRI T22/T23 helicopters. The results were satisfactory: all the properties of the aluminum beam were identified within acceptable margins of error (1 - 7%) and the characterization of the two helicopter blades is in agreement with the expected data.

Two main criticalities have been highlighted during the work: (i) the mass identification algorithm is highly sensitive to the imposition of total mass and center of mass constraints, (ii) the bending stiffness prediction strongly depends on the accuracy of displacement measurements.

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