Preliminary studies of flight sensing for loads and aeroelastic parameters estimation of the NGCTR-TD wing

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Abstract. The paper presents the preliminary analyses carried out to estimate the accelerometers and strain gauges optimal configuration for the in-flight natural modes and internal loads identification of the Next Generation Civil Tilt Rotor Technology Demonstrator (NGCTR-TD) wing.

The optimal accelerometers' configuration has been achieved with the aeroelastic model by taking into account the modal displacements of the targeted natural modes, requirements of space availability and accessibility. A further analysis has been set up to estimate the acceleration peak on the wing by using a continuous turbulence model with a von Karman power spectral density.

The optimal strain gauges' configuration has been achieved as a subset of an initial layout by using the Skopinski methodology, where quality ratios and percentual errors lead to the identification of redundant and irrelevant measurements. This approach aims to recover the flight loads on the wing from an optimal set of strain measurements during flight. The present work has been a numerical study. A verification of the final Load Evaluation Matrix (LEM) has been performed using a set of validation load cases.

1. Introduction

This work is focused on a preliminary study on the flight instrumentation of the innovative composite wing of the Next Generation Civil Tilt Rotor Technology Demonstrator (NGCTR-TD). The NGCTR-TD is one of the Fast Rotorcraft Integrated Aircraft Demonstrator Platforms foreseen in H2020 Clean Sky 2 Program.

The T-WING project is working on the composite wing of the NGCTR-TD planned to be flying in 2023, this covers design, manufacturing, qualification and flight-testing of the wing and moveable surfaces of the NGCTR-TD.

Regarding the topic of this paper, the objective to be pursued by flight testing is twofold: the evaluation of aeroelastic parameters and the evaluation of wing loads (shear force, bending and torsion moments). These two sets of results will be used to validate the aeroelastic model and the loads calculation tools, respectively. This objective will be reached by means of two sets of measurements in the wing: accelerations and strains. The acquired accelerations will be post
processed by using the auto-correlation technique and a rational approximation of the transfer function of the system to derive the aeroelastic parameters [1], [2]. The strain signals will be post processed and multiplied by a so called “Load Evaluation Matrix”, which is the result of a ground calibration test, to obtain shear force, bending and torsion moments pertaining a prescribed flight load condition.

The first publications on the evaluation of flight loads by means of strain gauges measurements were in 1948 [3] and in 1953 [4]. Even AMC No. 2 to CS 25.301(b) still recommends Skopinski work as an useful guidance on the calibration and selection of strain gauges installations in aircraft structures, which proves the high relevance of their work. The complete workflow until flight, for both aeroelasticity and loads activities, can be summarized in figures 1 and 2.

The present work is focused on the preliminary activity (highlighted with green dashed line) consisting in the selection and optimization of the measurements positions, directions, and type.

2. Accelerometers set-up

The goal of this activity has been to compute the optimal accelerometers’ configuration for the in-flight natural modes’ identification.

2.1. Methodology

An iterative process has been implemented with the following steps:

- A possible accelerometers configuration is achieved with the aeroelastic model taking into account the modal displacements of the targeted modes.
- The accelerometers configuration is then validated, by means of the wing digital mock-up (DMU), considering two main requirements: space availability and accessibility.

The optimal configuration is found when a possible accelerometers configuration is validated.

2.2. Analysis’ details and results

A preliminary analysis has been performed with a stick-beam wing aeroelastic model and the wing DMU. The analysis has considered both full-fuel and zero-fuel mass cases. The natural modes, selected as objectives of this analysis, are listed with their frequencies in table 1.

The accelerometers’ preliminary configuration achieved is shown in figure 3. The configuration consists of 15 vertical mono-axial sensors (yellow) and 3 lateral mono-axial sensors (red).

Since this is a preliminary study, the purpose of using mono-axial sensors at this point is not to define the type of sensor to use, but to highlight the direction of the measurement of interest.
Table 1. Objective natural modes.

| Mode Number | Description                  | Frequency [Hz] |
|-------------|------------------------------|----------------|
| 1           | 1st Symmetric Wing Bending   | 3.05           |
| 2           | 1st Symmetric Wing Torsion   | 6.23           |
| 3           | 1st Symmetric Wing For-Aft   | 6.39           |
| 4           | Morphing Surface Modes       | 12.03          |
| 5           | Flaperon Modes               | 48.25          |

Figure 3. Preliminary accelerometers’ configuration.

2.3. Estimation of Acceleration Range

In order to estimate the acceleration peak on the wing, a continuous turbulence model has been implemented based on the following hypotheses:

- Gaussian distribution of gust velocity intensities.
- Von Karman power spectral density with scale of turbulence $L$ (see equation 1).

\[
\Phi_I(\Omega) = \frac{L}{\pi} \left( 1 + \frac{8}{3} \left(1.339\Omega L\right)^2 \right)^{11/6} \tag{1}
\]

Cruise speed = 0.9 $V_D$, Mach = 0.37, Altitude: Sea level, Frequency range of analysis: 0-45 Hz. Scale of turbulence $L = 2500$ ft from normative [5].

The root-mean square of the incremental vertical acceleration at different points on the wing, for both full-fuel and zero-fuel, are shown in table 2.

Table 2. Turbulence incremental acceleration root-mean-square [$\Delta n_z$].

| Description     | Left Tip | Left Middle | Center Wing | Right Middle | Right Tip | A/C CG |
|-----------------|----------|-------------|-------------|--------------|-----------|--------|
| Without Fuel    | 2.06     | 3.16        | 2.46        | 3.02         | 2.03      | 2.43   |
| Full Fuel       | 1.71     | 2.21        | 1.94        | 2.19         | 1.77      | 1.91   |

From table 2, and considering the first frequencies ($\approx 3$ Hz, see table 1) of the wing modes, the acceleration peak on the wing is estimated to be lower than 10 g’s.
3. Strain gauges set-up

The goal of this activity has been to compute the optimal strain gauges’ configuration for the in-flight wing loads identification.

3.1. Methodology

The Skopinski approach has been used to achieve an optimal set of sensors and measurements as a subset of an initial layout. A summarized scheme of the methodology implemented is shown in figure 4.

![Figure 4. Strain gauges methodology.](image)

A 'virtual' calibration has been performed using the strains measurements and the integrated loads at each control section. After this, an iterative process is set up by using the Skopinski methodology (see Appendix A), where quality ratios and percentual errors lead to the identification of redundant and irrelevant measurements. This process ends once the optimal set of measurements for each control section is reached. At the end, the optimal set of measurements has been validated by means of the validation load-cases. This validation has been performed by estimating the applied loads using the suite of sensors determined in the previous steps.

3.2. Analysis’ Details

The preliminary analysis has been performed with a hybrid model, where the wing is modeled by a GFEM (Global Finite Element Model) and the other aircraft components are modeled using condensed mass and stiffness matrices (Nastran DMIGs).

The analysis has been based on the following load cases:

- 34 ISA (ambient condition): 25 LHD(Leonardo Helicopters Division)- provided LCs plus 9 LCs (Load Cases) obtained mirroring the anti-symmetric LCs.
- 34 COLD (-45° C OAT ): 25 LHD-provided LCs plus 9 LCs obtained mirroring the anti-symmetric LCs.
- 1 Ditching case.

Three control sections on the right wing have been chosen for the analysis. The control sections are shown in figure 5.

The strain gauges have been modeled using CQUAD4 elements with PSHELL properties of negligible stiffness.
Figure 5. Strain gauges, control sections.

From the 69 load cases, 35 (COLD + Ditching) have been used for calibration and 34 (ISA) have been used for validation. The strain gauges location at each control section is shown in figure 6.

Figure 6. Strain gauges location at each control section.

The definition of the strain gauges initial layout (measurements) depended on the strain gauges position and considering the typical structures’ behavior as follows:

- Spar webs: recovery of shear force and torsion.
- Spar caps: recovery of bending moment.
- Panels: recovery of torsion and bending moment.

3.3. Results
The first guess of strain gauges layout consists of 30 measurements and is shown in table 3. Besides, the optimal set of measurements for each control section is shown as well. On the table 3, the crosses mean an active measurement, while circles mean a dropped out measurement. CH, SP and SH stand for local chord-wise [normal], span-wise [normal], and strain gauge shear [shear]. This indicates the direction and type of measurement at each strain gauge location.

As shown on table 3, the optimal set of measurements for control sections 1, 2 and 3 consists of 13, 13 and 18 respectively, instead of the initial 30 measurements per section. The percent errors at each control section are shown in table 4.

After validation and calibration processes, the percent errors of the estimated wing loads have been lower than 2% at each control section.
Table 3. Strain gauges layout - first guess and optimal set.

| SG | First Guess | Control Section 1 | Control Section 2 | Control Section 3 |
|----|-------------|-------------------|-------------------|-------------------|
|    | CH | SP | SH | CH | SP | SH | CH | SP | SH | CH | SP | SH |
| 1  | X  | X  | X  | O  | O  | O  | O  | O  | O  | O  | O  | O  |
| 2  | X  | X  | X  | O  | O  | O  | O  | X  | X  | O  | X  | X  |
| 3  | X  | X  | X  | O  | O  | X  | X  | X  | O  | X  | X  | X  |
| 4  | X  | O  | O  | O  | O  | O  | O  | O  | O  | O  | O  | O  |
| 5  | X  | X  | O  | O  | O  | O  | O  | O  | O  | O  | O  | O  |
| 6  | X  | X  | X  | X  | X  | X  | X  | X  | X  | X  | X  | X  |
| 7  | X  | X  | O  | X  | O  | O  | X  | X  | O  | X  | O  | X  |
| 8  | X  | X  | O  | O  | O  | O  | O  | O  | O  | O  | O  | O  |
| 9  | X  | X  | X  | X  | X  | X  | X  | X  | X  | X  | X  | X  |
| 10 | X  | X  | X  | X  | X  | X  | X  | O  | X  | X  | X  | X  |
| 11 | X  | X  | X  | X  | X  | X  | X  | X  | O  | X  | X  | X  |
| 12 | X  | X  | O  | X  | O  | X  | O  | X  | X  | X  | X  | X  |
| 13 | X  | X  | X  | O  | O  | X  | O  | O  | X  | O  | O  | O  |

Table 4. Percent errors.

|                   | 1st Layout | Final Layout | Validation |
|-------------------|------------|--------------|------------|
|                   | AVG | MAX | AVG | MAX | AVG | MAX |
| Control Section 1 | HIGH | HIGH | 0.10 | 0.56 | 0.12 | 1.59 |
| Control Section 2 | HIGH | HIGH | 0.17 | 1.04 | 0.18 | 1.34 |
| Control Section 3 | HIGH | HIGH | 0.10 | 0.44 | 0.10 | 0.44 |

4. Conclusions
A preliminary analysis set-up of optimal accelerometers and strain gauges has been derived from FEA simulations. The optimal accelerometers configuration has been achieved with the aeroelastic model taking into account the modal displacements of the targeted modes. This setup has been validated by means of the wing DMU, considering two main requirements: Space Availability and Accessibility.

Five modes have been targeted in the accelerometers preliminary analysis.

Strain gages preliminary optimization is based on a “virtual (FEA)” calibration, which uses the methodology developed by Skopinski, Aiken and Huston.

The Skopinski approach has been implemented to reduce the number of measurements with reasonable percent errors by using indicators to drop out irrelevant and redundant measurements. The strain gauges calibration is intended to be a preliminary step before the real ground calibration to be made before flight.

Future steps in the NGCTR-TD program will be: update of the analyses to follow the design evolution; implementation of sensors and cables in the DMU, installation and ground calibration of strain gauges, sensors functionality checks, post process of flight data.
Appendix A. Skopinski-Aiken-Huston methodology for flight loads estimation

The methodology [4] is based on the relationship between a strain measurement and the loads (shear force $S$, bending moment $M$ and torsion moment $T$). Writing the loads at a generic section as function of $j$ strain measurements $\mu$ located at the same section (see equation A.1). Where the matrix $B$ is the so-called Loads Evaluation Matrix (LEM) and allows the evaluation of loads from strain measurements in general.

\[
\begin{bmatrix}
S \\
M \\
T
\end{bmatrix} = B\mu
\]  

(A.1)

With $\mu \in \mathbb{R}^{j \times 1}$ and $B \in \mathbb{R}^{3 \times j}$. It is important to notice the matrix $B$ has 3 rows linked to shear force, bending moment and torsion moment.

Considering only the shear force and the related entries in the LEM, it is possible to write the shear force as equation A.2 shows.

\[
S = \begin{bmatrix} b_{11} & b_{12} & \ldots & b_{1j} \end{bmatrix} \begin{bmatrix} \mu_1 \\ \mu_2 \\ \vdots \\ \mu_j \end{bmatrix} \Leftrightarrow S = \begin{bmatrix} b_{11} \\ b_{12} \\ \vdots \\ b_{1j} \end{bmatrix} \begin{bmatrix} \mu_1 \\ \mu_2 \\ \ldots \\ \mu_j \end{bmatrix}
\]  

(A.2)

Expanding the equation A.2 considering $n$ calibration loads with $n > j$, the equation A.3 is achieved. Using more calibration loads than strain sensors is equivalent to take into account additional terms (non linear) in the load recovering as shown in equation 4 in [4].

\[
\begin{bmatrix}
S_1 \\
M_1 \\
T_1 \\
S_2 \\
M_2 \\
T_2 \\
\vdots \\
\vdots \\
S_n \\
M_n \\
T_n
\end{bmatrix} = \begin{bmatrix}
\mu_{11} & \mu_{12} & \ldots & \mu_{1j} \\
\mu_{21} & \mu_{22} & \ldots & \mu_{2j} \\
\vdots & \vdots & \ddots & \vdots \\
\mu_{n1} & \mu_{n2} & \ldots & \mu_{nj}
\end{bmatrix} \begin{bmatrix}
b_{11} \\
b_{12} \\
\vdots \\
b_{1j}
\end{bmatrix} \begin{bmatrix}
b_{21} \\
b_{22} \\
\vdots \\
b_{2j}
\end{bmatrix} \ldots \begin{bmatrix}
b_{nj} \\
\end{bmatrix}
\]  

(A.3)

Noticing that $C = B^T$, the load evaluation matrix can be calculated via least squares as shown in equation A.4.

\[
L = \Gamma C \iff \Gamma^T L = \Gamma^T \Gamma C \iff C = (\Gamma^T \Gamma)^{-1} \Gamma^T L \iff B = \left((\Gamma^T \Gamma)^{-1} \Gamma^T L\right)^T
\]  

(A.4)

The matrix $L$ contains the shear force, bending moment and torsion moment for a every calibration load. Calibration loads must guarantee no linear dependency.

The methodology is aimed at optimizing type, number and position of strain sensors starting from a high number of installed sensors of different typology. The criteria that will be used are based on the computation of some quantities useful for establishing the redundancy and the relevancy of each measurement [6].

For each section, the difference $\varepsilon$ between the loads obtained from measurements and the loads applied during calibration (calculated by means of integration of forces) can be obtained. In the case of shear force, the difference $\varepsilon = \bar{S} - S$ is a column vector containing, for each calibration condition, the difference between the two shear force values. Analogous results can be obtained
for bending and torsion moments.

The probable error of shear force estimation is given by equation A.5. Where \( n \) is the number of calibration loads and \( q \) is the number of coefficients \( b \) in the shear equation. The equations for bending (PEB) and torsion (PET) are analogous.

\[
PES = 0.6745 \sqrt{\frac{\sum \varepsilon_i^2}{n - q - 1}} \tag{A.5}
\]

Probable errors for each coefficient of the equation can be defined as equation A.6 shows.

\[
\begin{bmatrix}
PES(b_{11}) \\
PES(b_{12}) \\
\vdots \\
PES(b_{1j})
\end{bmatrix}
= PES \begin{bmatrix}
\sqrt{m_{11}} \\
\sqrt{m_{22}} \\
\vdots \\
\sqrt{m_{jj}}
\end{bmatrix}
\tag{A.6}
\]

Where the terms \( m_{kk} \) with \( k \in \{1, 2, ..., j\} \) are the diagonal terms of the matrix \((\Gamma^T \Gamma)^{-1}\). Similar relations are applicable to bending and torsion moments. In order to find if a measurement is irrelevant or redundant, the following checks can be made. Redundancy is found if large probable errors are detected for LEM coefficients. On the other hand, an irrelevant measurement has a small LEM coefficient in comparison with its probable error and with other LEM coefficients. To do so, a quality ratio (see equation A.7) can be defined to establish relevancy.

\[
QR = \frac{b_i}{PES(b_i)} \tag{A.7}
\]

Once a redundant or irrelevant measurement is detected, a new computation of the load evaluation matrix can be made after dropping out the identified measurement in order to improve the loads estimation.

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**Disclaimer**

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