NEW METHODS FOR ROTOR TRACKING AND BALANCE TUNING AND DEFECT DETECTION APPLIED TO EUROCOPTER PRODUCTS

by

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ABSTRACT

The purpose of helicopter rotor "track and balance" adjustment is to provide a low vibratory level in 1 per rev along the 3 aircraft axes, to ensure optimized crew and passenger comfort.

This adjustment is performed systematically after manufacturing, that is to say before the first flight as well as after any rotor maintenance intervention. It can also be carried out at any time at the customer's request.

This document introduces a new rotor adjustment methodology based on a learning and adjustment technique by neural networks, ensuring minimized fuselage vibration (on first harmonics of the rotor frequency) in as many points as desirable, along the three axes, and in one or two adjustment flights only.

The method is only based on acceleration measurements along three axes, at a few points on the aircraft, to achieve rotor tuning. In particular, blade track measurement is not necessary. The adjustment values obtained through this method are entirely in keeping with the manufacturer's specifications.

Firstly, this paper details the general rotor operating physical assumptions (isotropy, superimposition principle, linearity, …) on which the adjustment algorithms are grounded. Non-linearity can also be included in the algorithms if a sufficient data base is available.

Then, we will present the mathematics algorithms adopted for the learning and adjustment phase, as well as the software program created based on these algorithms.

Based upon test results achieved on a 10T helicopter, this software is then implemented for the adjustment of an intentionally misadjusted set of blades. Some of these test results are presented to illustrate the efficiency of the method.

INTRODUCTION

The reduction of helicopter vibrations has traditionally been a difficult task to achieve. The oscillatory motion of the fuselage has been a concern for several reasons:

- crew and passenger fatigue,
- high-cycle fatigue of different components, low reliability and high maintenance costs,
- low performance of different weapon systems (Difficult to use sights, difficult to point missiles,...)

The major new development programs still present high risks as far as helicopter dynamics are concerned. The main industrial motivations for the improvement of helicopter vibrations are:

- helicopter acceptance in the future (comfort, weapon system platform stability) will impose low vibration levels (0.10 g → 0.05 g → 0.03 g),
- extended flight envelope (speed, load factor), wide range of payloads and fuel loads, requiring high performance antivibration devices for easy flying,
- dynamics problems during development can lead to costly development delays and impose fundamental modifications in the aircraft design.
- The objective of every helicopter manufacturer is to design the new rotorcraft so as to enable «flying right from the drawing board» with minimum development time.

Many vibration control systems have been developed to counter the N-per-rev (N: number of blades) loads transmitted by the rotor to the structure. Now, the new generation of helicopter, like the EC155B (Figure 1), has very low vibration levels (lower than 0.1g on N-per-rev) (Figure 2). These low-levels could be ensured owing to:

- the blades and rotor optimization (Figure 3 & 4)
- the dynamic adaptation of the structure by shake test (figure 5)
However, very little attention was paid to other rotor harmonic frequencies transferred to the structure only in case of blade dissimilarities. Most efforts have been focused on the stability problems induced by blade dissimilarities as proved by the papers referred to herein.

Higher speeds and higher loads on blades combined with the search for better comfort will lead to the study of loads other than N-per-rev and not only stability problems.

Although small, these harmonic loads can become a concern for passengers through fuselage structural response, vibration control system resonant frequencies.

To reduce these harmonics it’s necessary to tune the track and balance of the rotors. This paper describes the new rotor tuning STEADYCOPTER® system developed by Eurocopter.

ORIGIN OF HELICOPTER VIBRATIONS

There are many causes for helicopter vibrations such as rotors, shaft gears, engines. These vibrations have an almost constant frequency due to the constant speed of rotating parts. The frequency range for comfort is from a few Hz to a few hundred Hz. There are also random vibrations from the airflow exciting the tail surfaces called « Tail shake ».

The different sources of vibrations are pointed out on Figure 6. In this paper, we will consider main rotor vibrations only. Vibratory response of the blade at its passing frequency is a natural behavior of any rotor. In hover, the aerodynamic loads acting on the blades are constant as a function of azimuth and no vibratory loads are generated on the hub.

In forward flight, the air-load on the blades varies during rotation due to the relative wind and incidence imposed by pitch. The loads on each individual blade are periodic at the frequency, which is a multiple of one-per-rev.

The dynamic response of the blade is dependent on the fundamental blade characteristics like blade natural frequencies, damping and mode shapes. The dynamic loads can be amplified or attenuated by the blade dynamics and transmitted to the rotor hub. The rotor is a filter with some canceling and some reinforcing components.

The basic mechanism of helicopter vibrations is shown in Figure 7. Another mechanism of vibrations appears when blades are not identical. Each blade is still slightly different from the other and cannot be fitted to the aircraft before being balanced. All can have consequences on the dynamic behavior and on cabin vibrations. These non-isotropic rotor vibrations can become important for modern helicopters when basic N-per-rev (N - Number of blades) is over-reduced. In these conditions, the resulting non-isotropic levels through the airframe can become similar to N-per-rev. Vibrations levels and their association produces a beating phenomenon at low frequency, which can be disturbing for the crew.

BLADE BALANCING INDUSTRIAL METHOD

Manufacturing errors or various damages can induce blade dissimilarities. Although produced on an industrial basis, composite blades vastly rely on worker’s rigor and skill to ensure the required quality. Many inspections are made at each manufacturing stage (weight, mechanical properties, mold temperature, holographic inspection, ...). Each blade is still slightly different from the others and cannot be fitted to the aircraft before being balanced.
Blade defects may be of different types: weight, span-wise and chord-wise e.g. position, span-wise weight distribution, airfoil shape, blade twist, leading and trailing edge shape. All can have consequences on the dynamic behavior. Therefore, a short presentation of blade balancing may be useful prior to the presentation of work on rotor anisotropy.

First, all blades must have the same first moment of inertia. This adjustment is made on scales and must be very accurate to obtain the same centrifugal force for all blades. Adjustment weights are added to the blade tip along the pitch axis (25 % chord).

The blade is then tested on a rotor dynamic balancing stand. This rotor uses three blades (even for four-bladed helicopters): the blade to be balanced, a master blade and a companion blade. The master blade is representative of the "average" production blade. Its role as reference makes it very valuable and it must be protected from rain and dust. The companion blade is less important, it is used to check possible changes in the rotor behavior.

The goal is to obtain, for all blades, the same track (height $H_θ$) and control loads (pitch moment $M_θ$) for the whole pitch range through pitch rod length, trim tabs and dynamic weights (Figure 8).

At low pitch, the pitch rod length is adjusted so that the tested blade has the same track as the others. This change in blade angle-of-attack is called $\Delta I$. Track is then recorded at high pitch.

Also at low pitch, the trim tab is deflected to obtain the right control loads. Tab deflection has almost no direct consequences on lift but it twists the blade and changes the pitch thus playing on control loads (nose down for downward tab deflection).

At high pitch, the dynamic weights are moved to get the same blade tracking and control loads. Dynamic weights are placed at blade tip symmetrically to the pitch axis. Weights produce a pitch-proportional moment due to the centrifugal forces on them (nose down moment for weights moved forward) (Figure 9). At low pitch, the centrifugal forces are almost parallel to the blade and do not generate any pitching moments.

Perfect adjustment is seldom achieved but a compromise on all parameters enables to get all the blades in a very narrow window as concerns track and loads whatever the pitch. Despite the accuracy of these tests, minor corrections to pitch rod length and tab deflection are still necessary on the aircraft due to the rotor hub and in order to obtain a satisfactory compromise between hover and forward flight (which cannot be simulated on the stand).

Balancing the rotor is achieved by adding weights on sleeves. For blade weights and first moment of inertia defects, rotor setting remains correct for all flight conditions.
The other three defects studied are difficult to balance because the generated load changes with helicopter speed and power. Figure 9 shows an example for a static stiffness defect of a lead-lag damper. The modulus of the one-per-rev load is plotted as a function of the advance ratio. The rotor has been balanced in hover for a given power. For other advance ratios the rotor presents phase-and modulus-changing loads.

**Figure 9**

![Figure 9: Example for a static stiffness defect of a lead-lag damper](image)

In hover, for a different aircraft weight, the imbalance reappears. This example explains that for problems related to lead-lag dampers, the rotor tuning depends on power and advance ratio.

**ROTOR BALANCING ON AIRCRAFT**

Balancing the rotor on a helicopter requires 3 to 4 well-defined aircraft configurations and two accelerometric measurements.

Typically the 4 configurations are:

- on the ground
- in hover
- cruising speed level flight
- high speed level flight

Both accelerometers are mounted in the fuselage or on the main gearbox, depending on the aircraft: one vertical and the other lateral. The first one being more indicative of a track problem and the second of a balance problem.

The three ways to balance the aircraft are: length of pitch change rod, tabs and weights on rotor sleeves.

Track tuning often requires some compromise between hover and forward flight.

Balancing also requires compromise, a perfectly hover-balanced rotor may cause problems in forward flight since all defects are corrected by weights but all type of defects do not create the same imbalance for the whole speed range.

This balance methodology is well adapted to current helicopters. For future high speed and low vibration aircraft, we should analyze whether this methodology is to be improved.

**NEW ROTOR TUNING SYSTEM: STEADYCOPTER®**

**Introduction**

The purpose of the system is to determine the adjustment parameters of the rotor by measuring the vibration levels in the cabin. The parameters suggested must ensure a low vibration level on the first harmonics of the rotor frequency. The system must be able to adapt to any type of aircraft.

The system is based on a neural networks approach. Indeed a neural network can easily model the transfer function between the adjustment parameters of the rotor and the vibration levels in the cabin on the first harmonics.

**Model**

In the document, the blades are indexed 1 to N, where N is the number of blades of the rotor. The adjustment parameters are noted $\alpha_j^i$ where $i$ represents the index blade and $j$ represents the parameter type (weight, pitch rod, tab). The Fast Fourier Transform coefficients of the cabin vibrations are noted $\gamma_{ah}$ where $a$ represents the accelerometer index and $h$ represents the harmonic.

For each aircraft, the vibration levels in the cabin can be written as:

$$\gamma_{ah}^h = H(\alpha_i^j)$$

where $H$ is the transfer function between the adjustment parameters and the vibration levels. So the system will seek to model this function.

**Neural network**

In order to ensure a good identification of $H$, the Feed-Forward network (Figure. 11) has been chosen. These networks enable almost any type of continuous function to be modeled (linear or not linear).
The neural network contains layers of cells. These cells, called neurons (by analogy with the human brain), process the data coming from the preceding layer and propagate it in the following layer. The layers are connected using connections having each one a weight. These weights enable the effect of each neuron within the data processing to be balanced. They are computed during the learning phase.

The left layer is called input layer while the right layer is called output layer. In our case the input layer corresponds to the adjustment parameters and the output layer to the FFT coefficients of the vibration levels in the cabin.

**Learning**

The learning phase enables the connection weights to be determined. After this procedure the network simulates the transfer function between the adjustment parameters and the vibration levels in the cabin.

To carry out the learning, it is necessary to collect representative learning couples of the application field. These couples consist of an input vector $\alpha$ (adjustment parameters) and an output vector $\gamma$ (vibration levels). These vectors satisfy the relation:

$$\gamma = H(\alpha)$$

Where $H$ is the transfer function of the system to be modeled.

In the STEADYCOPTER® system, the learning couples are given by an intentional misadjustment of the rotor and by measuring the vibration levels associated.

The algorithm applied for the learning phase uses the equations of the extended Kalman filter, that decreases the measurement noise effect.

In order to reduce the number of learning flights some hypotheses are necessary:

- superposition: the effect of each adjustment parameter is independent.
- linearity: the FFT coefficients of the vibration levels in the cabin are proportional to the adjustment parameters.
- isotropy: for each blade, each parameter type has the same effect on the vibration levels with a different phase (geometrical angle between the blades).

Only four flights are carried out for the learning:

- a reference flight
- a flight with a weight misadjustment
- a pitch rod misadjustment
- a tab misadjustment

Each flight has four specific configurations during which vibration measurements are taken. These configurations are typical of the aircraft use:

- Ground
- Hover
- 100 kts speed
- MCP

After having completed the flights, the whole learning couples are generated with the flight measurements

**Optimization**

When a new aircraft rolls off the line, or after rotor replacement, the rotor must be re-adjusted.

This phase consists in determining the adjustment parameters, which minimize the vibrations in the cabin by use of the neural network computed in the learning phase. The STEADYCOPTER® system proposes the set of parameters which optimizes the vibration levels.

**- How to find adjustment parameters?**

Each parameter has its own effect:

- weight: an unbalance of the rotor only generates vibration levels with the rotor frequency
- pitch rod: the track generates all the harmonics of the rotor frequency
- tabs: generate low vibration levels in flight configuration at low-speed.

The number and the location of the accelerometers are deciding for the quality of the optimization phase. The location and the orientation of the accelerometers enable an unbalance misadjustment to be distinguished from a track misadjustment.

The number of harmonics will also refine the quality of the parameters suggested by the system.
The research for the parameters is carried out by minimizing the function:

$$\left\| H(\alpha^j_i) + \gamma^h_a \right\|^2$$

where $\alpha^j_i$ is the adjustment parameter to be determined and $\gamma^h_a$ is the vibration level in the cabin before adjustment.

By using the effect properties, each parameter can be optimized separately. So, the risk to correct an unbalance with track (and vice versa) is avoided.

**FLIGHT TEST DATA**

The learning and optimization flights were accomplished on a 10T helicopter.

*test planning*

Four flights are necessary for the learning phase:
- reference flight: rotor well tuned by a traditional method
- flight with a weight misadjustment: +1Kg on blade 1
- flight with a pitch rod misadjustment: +20 notches on blade 3
- flight with a tab misadjustment: +10 ° on blade 4

Between the learning phase and the optimization phase, the rotor is intentionally misadjusted. Thus the aircraft has a high vibration level in the cabin. This level will be computed by the system to find the applied misadjustment.

Six accelerometers were located in the cabin:
- pilot sit: Zpil
- copilot sit: Ycop & Zcop
- under the rotor shaft: Xbac Ybac & Zbac

*learning*

The increments of the vibrations in the ground configuration generated by the successive misadjustments are presented on Figure 12 to 15.
Indeed the unbalance is characterized by a revolving force in the plane of the rotor disk. It produces little vibration in Z near the aircraft center of gravity.

**Optimization**

In order to test the system, the rotor was intentionally misadjusted with the following parameters:

<table>
<thead>
<tr>
<th></th>
<th>Mass (g)</th>
<th>Pitch Rod (notches)</th>
<th>Tabs (°)</th>
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</thead>
<tbody>
<tr>
<td>Blade 1</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Blade 2</td>
<td>700</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Blade 3</td>
<td>0</td>
<td>0</td>
<td>8</td>
</tr>
<tr>
<td>Blade 4</td>
<td>0</td>
<td>-15</td>
<td>0</td>
</tr>
</tbody>
</table>

The parameters suggested by the system to correct the vibration levels are:

<table>
<thead>
<tr>
<th></th>
<th>Mass (g)</th>
<th>Pitch Rod (notches)</th>
<th>Tabs (°)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Blade 1</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Blade 2</td>
<td>-770</td>
<td>0</td>
<td>-3</td>
</tr>
<tr>
<td>Blade 3</td>
<td>-130</td>
<td>2</td>
<td>-8</td>
</tr>
<tr>
<td>Blade 4</td>
<td>0</td>
<td>-16</td>
<td>-2</td>
</tr>
</tbody>
</table>

These parameters are almost identical to the parameters applied before the optimization. The system succeeded in correcting the vibration levels (Figure 20 to 23) while correctly distinguishing the unbalance from the track.

**CONCLUSION**

Most helicopter manufacturers focus mainly on rotor and fuselage dynamics at N-per-rev (N: number of blades). This optimization seems to be insufficient for low-vibration aircraft due to anisotropic rotors. Low vibration levels on non-N-per-rev harmonics (first harmonics principally) are deciding for crew comfort.

With the new STEADYCOPTER® system, the “track & balance” can easily be performed by only measuring
vibrations in the cabin. The flight tests showed the pertinence of the system. Integration in Eurocopter products is in progress.

For the future:
- non-linearity of the adjustment parameter effect will be included to increase the adjustment quality.
- introduction of a default detection method for rotor systems.

REFERENCES