ANALYTICAL METHOD TO DETERMINE DYNAMIC LOADS ON REDUCED SCALE HELICOPTER BLADES AT ONERA

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Abstract

An analytical method has been developed to provide real-time values of the inertia and aerodynamic loads on a helicopter blade during a windtunnel experiment. This method is named MACFAIR, which is a French acronym for "Analytical Method to Compute Rotor Aerodynamic and Inertia Forces". The aerodynamic loads are derived from the equations of motion for each single blade, which are governed by the variations of the blade flapping and lead-lag angles and the moments of inertia of the various rotating systems. Determination of the aerodynamic torque provided to one blade in a continuous mode is a key decision factor in the assessment of the efficiency of a blade profile being submitted to changing wind conditions as it rotates. The rotor loads and moments at rotor center are determined as well, which will help in the process of minimizing the vibration levels transmitted to the helicopter structure by the blades. To check the MACFAIR analytical method, the torque, necessary to drive the rotor, is calculated and compared to the torque measured by a torquemeter located on the rotor shaft and both values match very well. Comparison of the dynamic loading obtained by the analytical method and balance measurements corrected for inertia are very satisfactory too. This analytical method will improve the quality of the database offered to the ONERA windtunnel clients and the test productivity.

List of symbols

β : flapping angle of the blade
δ : lead-lag angle of the blade
Ω : hub rotational speed
θ : pitch angle of the blade
$\overline{Z}$: rotor lift coefficient

Introduction

ONERA GMT has been carrying out test campaigns on helicopter rotors and tilt rotors in the Modane-Avrieux S1 transonic windtunnel for over 30 years. These tests provide helicopter constructors and European research institutes with the data, which enables rotor performance, vibration levels, and acoustics, to be improved.

Over the years test means and methods have evolved considerably, and increasingly complex tests are now possible.

In line with previous improvements in methods, this article presents a new analytical technique developed in the ONERA Modane-Avrieux center in 2002. With this method it is now possible to calculate aerodynamic and inertia loads applied to a helicopter blade during its rotation. This method, based on the relationship of the Dynamics and theorem of kinetic moment as applied to flapping and lead-lag motions, enables two critical parameters to be determined. The first one is the aerodynamic torque generated by the blade, and the second one, the global unsteady aerodynamic and inertia loads and moments at the rotor center; this term is henceforth called dynamic loading in this paper. The aerodynamic torque is in effect directly linked to rotor performance (power supplied to the rotor) and knowledge of dynamic loading is the critical factor in order to quantify vibration levels, which create metal fatigue and are a source of discomfort for passengers. A drastic reduction in these vibration levels is one of the major challenges facing helicopter constructors for the next years (Ref 1).

Study objectives

A helicopter rotor is composed of two main elements: the hub and the blades.
The ONERA S1 Modane hub, like a real helicopter hub, is divided into a fixed and a rotating part. Interfacing between these two parts is carried out by a swashplate. Inclining the swashplate with three hydraulic jacks does the pitch control of the blades. Figure 1 shows the diagram of the articulated helicopter rotor used in S1 Modane.

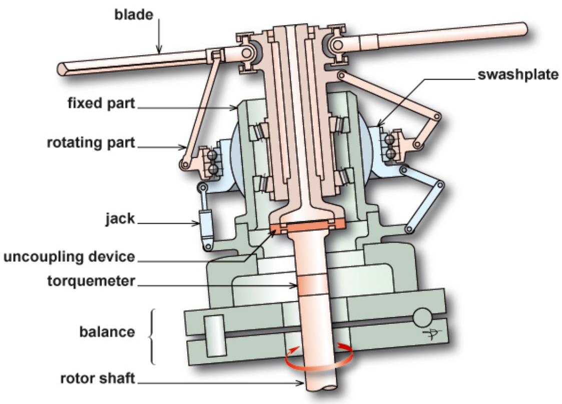

Fig. 1: Diagram of S1 Modane articulated helicopter rotor

A large number of blades have been tested on this rotor over the past fifteen years and their geometry and internal structure have become more and more complex. Complex chord law blades with non-linear twisting have replaced rectangular blades with linear twist. In addition the number of profiles used on the same blade have increased and the internal weight distribution has been progressively optimized in order to reduce the unsteady loads and moments generated by the blades at rotor center.

Figure 2 shows the shapes of two helicopter blades tested at S1 Modane in 1988 and 1999 respectively. The rectangular 7A blades with linear twist are mainly composed of three profiles (OA213, OA209 and linking profile in-between). The ERATO blades, on the other hand, have complex chord law and a succession of five profiles from blade root up to blade tip. The ERATO blades were specifically designed to reduce the noise generated by the blade/vortex interaction.

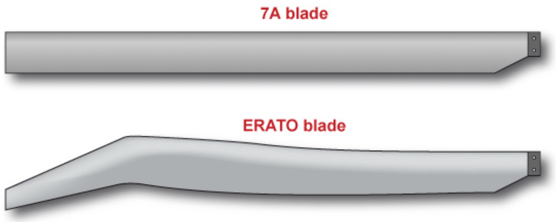

Fig. 2: Top view of 7A and ERATO blades

In contrast to the beginning of the 1980s, when measurement of the static aerodynamic loads by means of a balance and torque meter were considered sufficient (Ref 2), nowadays the measurement of unsteady aerodynamic phenomena applied to each blade in rotation is necessary. This knowledge helps in identifying the geometric parameter responsible for the improvement observed in this or that blade configuration.

To measure these local phenomena, blades used in tests are equipped with more and more pressure sensors (170 pressure sensors in the most recent test campaigns). The experimental data, provided by these sensors, gives extremely useful information on the local pressures affecting the different profiles on a blade. Important improvements have thus been made, and will continue to be made, for many years. However, a lack of space and the mechanical resistance of the materials limit the number of sensors that can be used, and the global aerodynamic vector applied to the blade in rotation remains difficult to determine.

The goal of the analytical method presented in this paper is in no way to bypass the measurements based on the pressure sensors, but rather to complete them in order to gain access to the global aerodynamic vector. This knowledge then enables the determination of the aerodynamic torque generated by the blade in relation to the azimuth and the dynamic loading applied by the blades to rotor center.

Field of application

The MACFAIR analytical method is applied to hubs with the following characteristics:

- Articulated hubs, with, from hub center to blade tip, lead-lag, flapping, and pitch axes;
- Identical lead-lag and flapping excentricity (distance between rotor rotation axis and the articulation axis in question);
- Possibility of modeling the hub by undeformable systems (including the blades), as defined in the next paragraph.

Systems considered

For the analytical method , the hub and the blades are shared in various undeformable systems to take into account all the degrees of freedom between these different parts.

Figure 3 presents these systems and figure 4 defines more precisely the different degrees of freedom present between systems S1.i, S2.i and S3.i.

- Systems S1.i correspond to the blades plus the external part of the pitch arm also named sleeve. These systems are denoted by movements in pitch θ, flapping β, lead-lag δ and complete hub rotation Ω;
- S2.i systems are the pitch shafts. They are connected to the external part of the pitch arms by a ball bearing and to the drag pins by a pivot link. The pitch shafts are denoted by movements in flapping, lead-lag, and complete hub rotation;
- The drag pins S3.i are connected to the rotating part of the hub by a pivot link with lead-lag dampers. Their motions are lead-lag and complete hub rotation;
- System S4 is the hub rotating part with the exception of systems S1.i, S2.i and S3.i. It is connected with S3.i and S5 systems but also with S1.i systems thanks to the pitch links. S4 motion consists only of complete hub rotation;
- Lastly system S5 refers to all the fixed parts of the hub and to the weighed part of the balance. Two strut bearings and the swashplate bearing carry out the pivot link between systems S4 and S5.

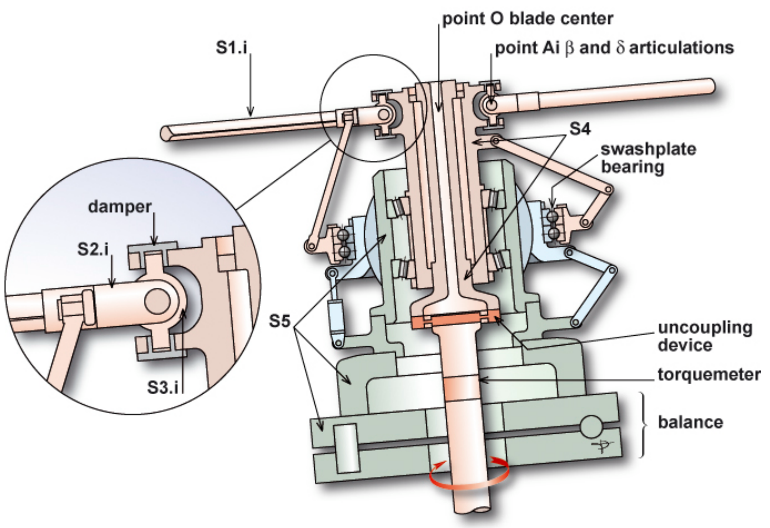

Fig. 3: Undeformable systems considered by the analytical method

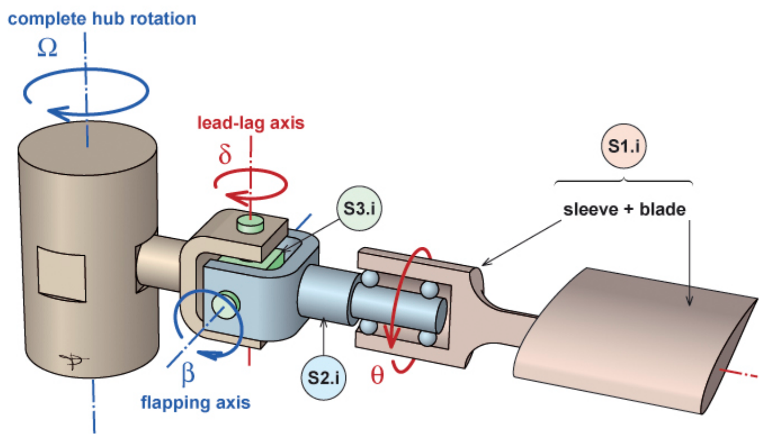

Fig. 4: Degrees of freedom between systems S1.i, S2.i and S3.i

Loads considered

The diagram in figure 5 presents the loads taken into account by the analytical method for each system.

For the blades and the external parts of the pitch arms also named S1.i systems, forces considered are aerodynamic forces, inertia forces related to S1.i motions, tare weight and link loads between systems S1.i and S2.i and between S1.i and S4.

For the pitch shafts S2.i, situation is very similar with aerodynamic forces, inertia forces, tare weight and link loads between S1.i and S2.i and between S2.i and S3.i.

For the lead-lag pins S3.i, aerodynamic forces, inertia forces, tare weight and link loads have been considered too.

For the rotating part S4, forces taken into account are aerodynamic forces, inertia forces, tare weight and rotor shaft forces transmitted in torque and lift directions by the uncoupling device. Furthermore link loads between S3.i and S4, between S4 and S5 and between S4 and S1.i via the pitch links are considered too.

Finally forces considered for the fixed part of the hub (S5 system) are tare weight, link loads between S4 and S5 and balance forces because system S5 is linked directly with the balance. There are no aerodynamic forces on system S5 because it is located inside hoods on S1 Modane test bench and there are no inertia forces because it is a fixed part.

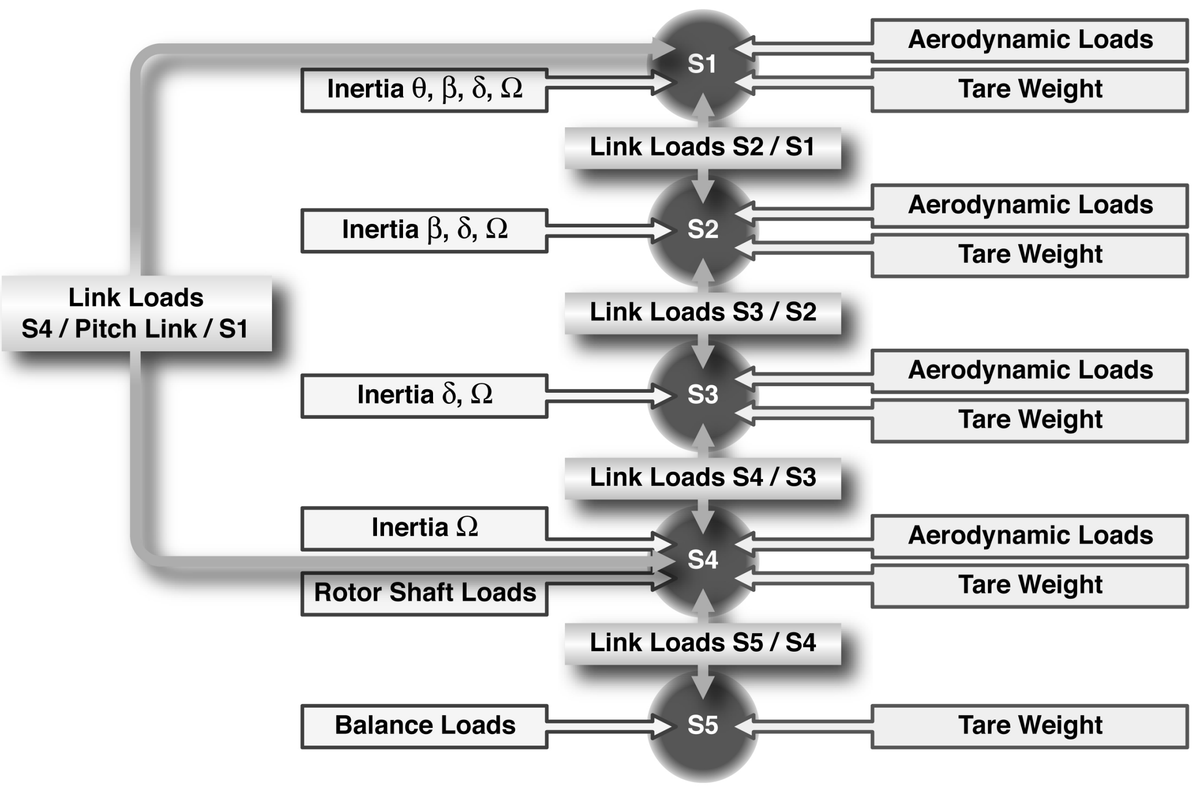

Fig. 5: Forces considered for each system

Equations

A flowchart showing the different steps involved in the analytical method is given in figure 6.

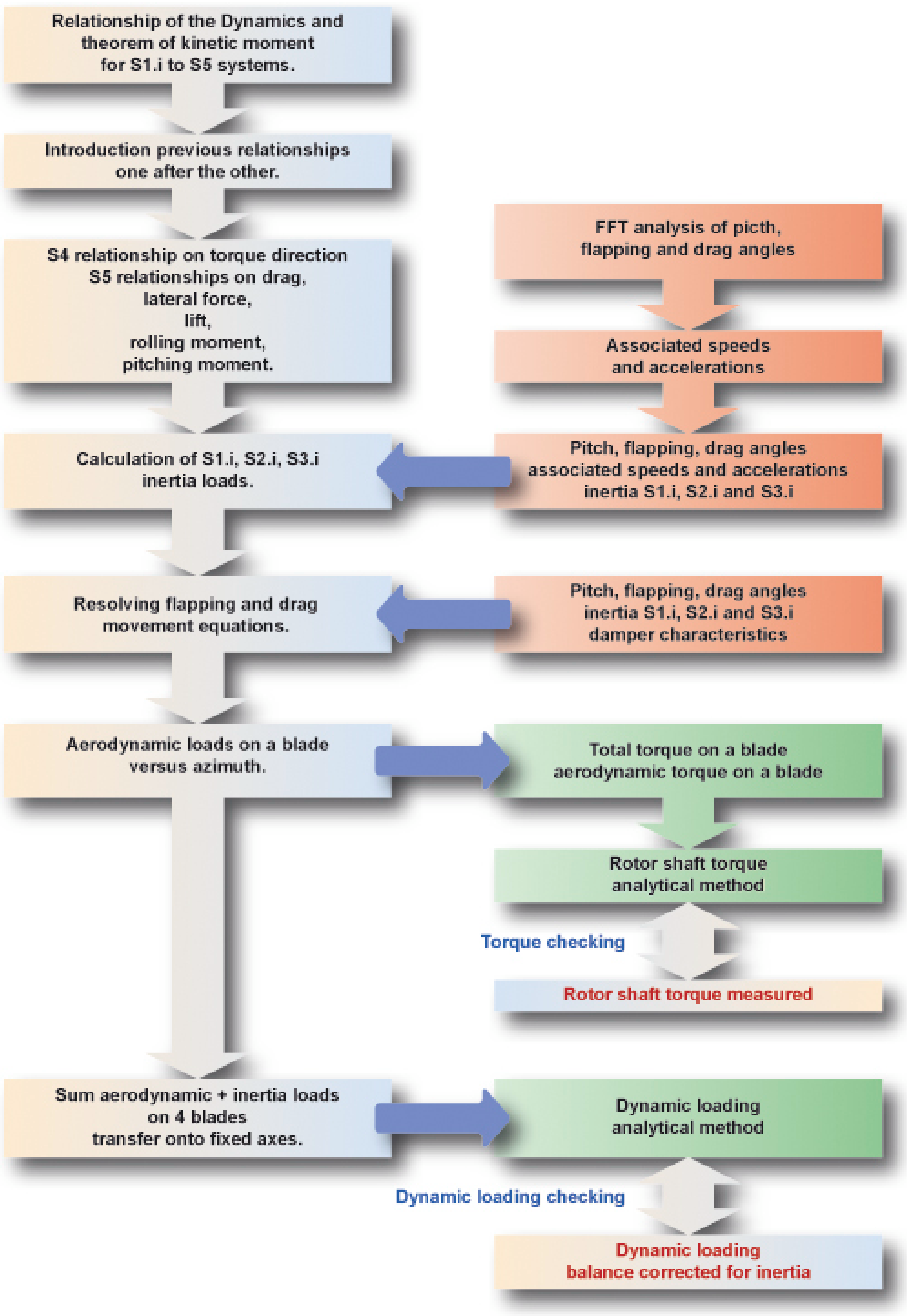

Fig. 6: Descriptive Flowchart of the Analytical Method

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The first step of the analytical method consists of writing the relationship of the Dynamics and theorem of kinetic moment for all the systems S1.i to S5.

Then the following steps consist of:

- Introducing the relationship obtained for each system in series, one after the other, starting from systems S1.i to system S5. This process eliminates all the link loads mentioned in figure 5. During this process the flapping and lead-lag movement relations are obtained;
- Writing the relationship in torque direction for system S4;
- Writing the S5 relationships based on drag, lateral force, lift force, rolling moment and pitching moment components. These relationships, which only include aerodynamic loads and inertia terms, enable the determination of the dynamic loading at rotor center;
- Determining an analytical expression, by means of a F.F.T. analysis, of the pitch, flapping and lead-lag angles. Their associated angular speeds and accelerations are calculated by numerical derivations. S1.i, S2.i and S3.i inertia matrices are estimated by simplified modeling and the characteristics of the lead-lag dampers are determined by a special test bench. With all these inputs, inertia loads on S1.i, S2.i and S3.i systems are computed and considering these inertia loads and flapping and lead-lag relations, Aerodynamic loads blade per blade are computed;
- The aerodynamic torque and the total torque (aerodynamic + inertia) supplied to one blade are then accessible;
- The dynamic loading at rotor center is determined by adding together the aerodynamic and inertia loads obtained on the four blades and transferring onto fixed axes.

Equations are established taking into account all of the degrees of freedom that exist between the different systems, with all the forces mentioned in figure 5 and whatever the inertia characteristics and the positions of the center of gravity of the different systems. The complexity of the obtained equilibrium equations is considerably increased, but the number of simplifying assumptions is drastically reduced in relation to what is commonly considered acceptable in publications.

Test means

After a brief description of the S1 Modane windtunnel, this section presents the main characteristics of the helicopter rotor test bench.

S1 Modane Windtunnel

S1 Modane is a continuous transonic windtunnel with a maximum power of 88MW. For helicopter rotor tests the maximum airspeed is 105m/s and this can go up to 205m/s with tilt rotor tests. However speeds of about Mach 1 are attainable in this windtunnel which is equipped with three test carts. Two tests can thus be prepared at the same time as a test is done. These test carts have a length of 14m and a diameter of 8m. Figure 7 is a diagram of this windtunnel with its impressive size, the settling chamber measures 24m in diameter for example.

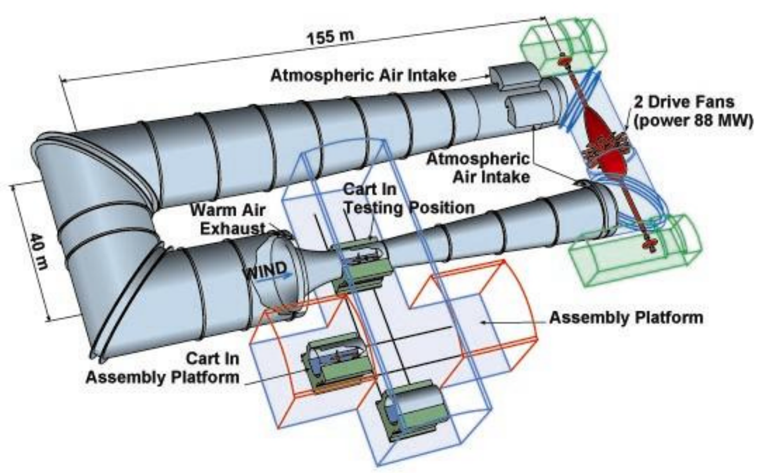

Fig.7: The ONERA S1 Modane windtunnel

The helicopter rotor test bench

The helicopter rotor test bench enables rotor and tilt rotor tests to be carried out on isolated rotors with a maximum diameter of 4.2m.

The main characteristics of this bench are:

- Clockwise or anti-clockwise rotation;
- Rotation speed between 0 and 1150 tr/mn;
- Maximum power of 500 kW;
- Maximum torque of 7000 N.m at 680 tr/mn;
- Rotor shaft tilt angle between +20° and -95°;
- Accuracy of rotor shaft tilt angle ±0.02°;
- Stability of rotation speed during the acquisition phases ±0.2%;
- Maximum tilting speed of rotor shaft 2° per second;
- Emergency battery backup for rotor power in case of main power failure.

More detailed information about the ONERA S1 Modane helicopter rotor test bench is available in Ref 3.

The photo in figure 8 shows the test bench during tests on the European EUROFAR isolated tilt rotor in 1991. Only articulated 4-blade rotors have been tested up until now, but testing of 5-blade rotors, with HMR or BMR hubs is also possible on request.

Fig. 8: ONERA Helicopter Rotor Test Bench in the S1 Modane Windtunnel

Measuring techniques

The measuring techniques used to obtain input data for the analytical method (bench to determine the transfer functions of the lead-lag dampers, pitch, flapping and lead-lag angular sensors), or to give the data needed for cross-checking (balance, torque meter), are presented below.

Bench to determine lead-lag damper transfer functions

The transfer functions of the lead-lag dampers (stiffness and damping coefficients) make up a part of the input data for the analytical method. They are measured during the hub maintenance program before each test campaign thanks to a special test bench.

This bench also enables ONERA to check there is no separation between the metallic and rubber parts of the dampers. The existence of such a separation could lead to the rotor destruction.

Main details of this bench, developed by ONERA Modane in cooperation with EUROCOPTER are given in figure 9.

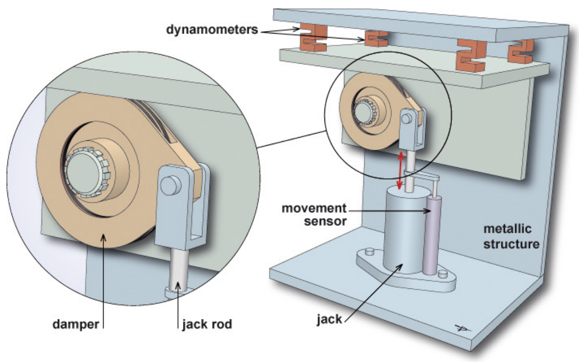

Fig 9: Diagram of lead-lag damper bench

This bench consists of:

- A hydraulic jack which generates a static or dynamic rotation of the damper;
- A movement sensor linked to the jack;
- A metallic structure which supports the jack, damper and four dynamometers.

The dynamometers and the movement sensor measure the force generated by the jack and the damper rotation angle respectively. The transfer function between these two quantities is determined both statically and dynamically, which then enables the damper stiffness and damping to be calculated for various frequencies. The four dampers with the closest characteristics are installed on the hub so as to guarantee identical static and dynamic blade behavior during testing.

Blade angular position sensors

The other input data necessary for the analytical method are the pitch, flapping and lead-lag blade angles, and their first and second derivatives (angular speeds and accelerations). The use of these speeds and accelerations in the different equations necessitates a very good accuracy on angle measurements. In order to achieve this, inductive sensors have been used since 1997. They have the following advantages compared to classical potentiometers:

- Their maximum working frequency is 20 Hz instead of 7 Hz for classical potentiometers. Taking into account the maximum rotation speed of 1150 tr/mn (19.2 Hz) for the helicopter rotor test bench, the inductive sensors are perfectly suitable;
- In contrast to the potentiometers, the use of these sensors avoids contact between the rotating and fixed parts. Their lifetime is therefore considerably longer than the time required for a test campaign;
- Their associated electronics are positioned in the rotating part. These electronics, defined by ONERA, give high output signals before crossing the slipring. The signal to noise ratio is therefore considerably increased.

The combination of these characteristics has led to an improvement in the measurement accuracy of the blade angle positions by a factor of 1 to 15, and maximum unreliability of ± 0.05° has now been reached.

For the test campaigns till 2002 only two blades (blades 1 and 3) were equipped with these inductive sensors. Therefore analytical method calculations assume for the moment that blade 2 behaves identically to blade 1, with a phase shift of 90°, and likewise blades 3 and 4. Starting from 2003 all four blades will be equipped with inductive sensors.

In addition to these sensors giving input data, unsteady measurements from the balance, torque meter and onboard accelerometers are used to check the analytical method. These measuring instruments are briefly described in the following paragraphs.

The balance

A non-rotating balance measures the loads and moments applied to the rotor apart from the torque which is measured by a torque meter. To protect the balance, a locking system is automatically activated whenever its capacity is exceeded.

The torque meter

The torque meter, which is situated on the rotor shaft, is surrounded by two uncoupling systems. These uncoupling systems transmit the torque, but at the same time are flexible enough in other planes to avoid short-circuiting the balance measurements. The residual lift load is taken into account by means of measurements from a strain gauge located on the upper uncoupling device.

All these measuring instruments (figure 10) enable a static measurement accuracy of ±1 % to be reached.

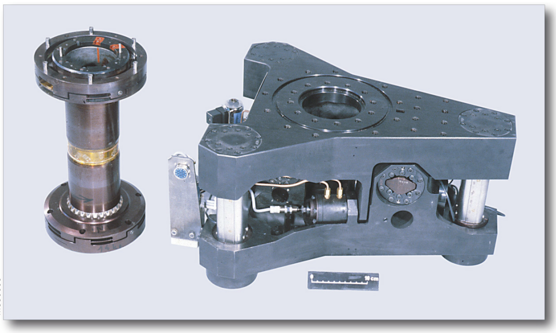

Fig 10: balance, torque meter and uncoupling devices

In addition to static load measurements, dynamic signals from these instruments are acquired at a rate of 256 points per revolution.

These torquemeter measurements directly give the change in rotor torque over one revolution as provided by the rotor shaft. Comparison of this quantity with the sum of the torques on the four blades, as calculated by the analytical method, provide torque crosscheck mentioned in figure 6.

On the other hand, checking of the dynamic loading (also mentioned in figure 6) is more complex since the balance dynamic measurements don't correspond directly to the dynamic loading at rotor center. In reality the balance not only measures the dynamic loads due to the blades (aerodynamic and inertia), but also inertia loads generated by small movements of S4 and S5 systems. To determine these latter inertia loads, accelerometers are installed on the hub, eight on the fixed part and ten on the rotating part.

Results obtained with the analytical method

On the graphs presented in this section the x-axis corresponds to the blade azimuth in degrees. During tests the rotation direction is clock-wise as viewed from above. The angle 0° corresponds to the blade in rear position, and 90° to the forward position.

Checking of torque calculations

As mentioned in the "equations" paragraph, the aerodynamic torque and the total torque provided blade per blade are computed and adding together the four total torque, rotor torque is determined. For blade optimization, aerodynamic torque provided to one blade is mandatory but rotor torque is important too because its comparison with torquemeter measurement provides a validation of the analytical method in this direction.

Both static and dynamic checks are possible. Such comparisons, with rotor torque calculated up to 5th harmonic, are shown in figures 11 and 12 for two test points performed at two different lift coefficients. Mean and dynamic values of the rotor torque, as measured by the torquemeter, are presented by the grey curves.

As expected lift differences, between the two test points, generate large torque changes. Agreement between static measurement (grey straight lines) and mean value of rotor torque as computed by the analytical method (black straight lines) is very satisfactory. For the database available, differences are lower than 5% for 63% of the test points and maximum deviations are 8% only.

Comparisons of dynamic levels are even more significant. Agreement between computation and measurement is very satisfactory too, particularly in view of the fact, mentioned previously, that measurement of the pitch, flapping and lead-lag angles required for the calculations are only done at the moment on two out of the four blades.

These comparisons give strong confidence in the analytical method for computations in torque direction. However these comparisons are done at rotor level and for blade performance optimization it is necessary to come back at blade level and to concentrate on aerodynamic torque generated by a blade.

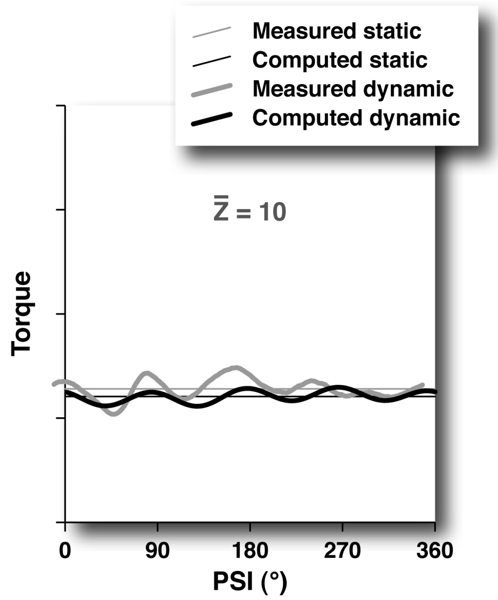

Fig. 11: Comparison rotor torque calculated / measured

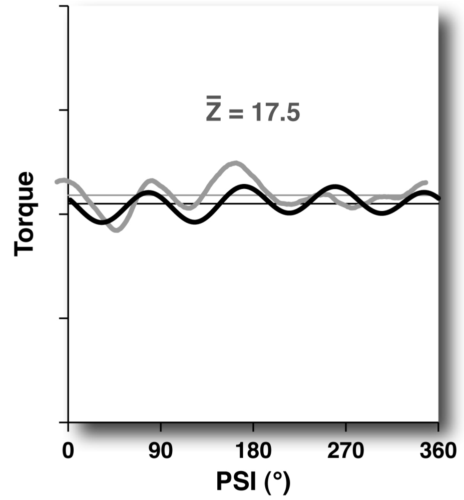

Fig. 12: Comparison rotor torque calculated / measured

Aerodynamic torque generated by a blade

The lead-lag equation draws on terms linked to the lead-lag damper characteristics, to inertia terms and to the torque of the aerodynamic loads generated by the blade. Knowledge of the blade angular positions enables the terms for the damper and inertia to be calculated, which in turn enables calculation of the aerodynamic torque.

Figure 13 presents the aerodynamic torque provided to one blade as computed by the analytical method using 3 harmonics (static, 1 per rev and 2 per rev) and 5 harmonics. "Modane" pitch control was used for this test point. This control cancels the 1 per rev lateral flapping and equalizes the 1 per rev longitudinal flapping and lateral pitch.

With 3 harmonics, aerodynamic torque evolutions versus azimuth are smooth and consistent with theoretical predictions obtained at ONERA Applied Aerodynamic Department. With 5 harmonics, evolutions versus azimuth have large fluctuations. This phenomenon can be explained by the presence of a term involving the lead-lag angular acceleration in the torque equation. The two successive derivations of the lead-lag angle used to calculate the acceleration, mean that the higher the harmonic the greater its importance in the equation. The accuracy for lead-lag angle was around 0.05° and it is not sufficient to guarantee aerodynamic torque results with 5 harmonics. Then only 3 harmonic results are used and actions have been scheduled to reach an accuracy of 0.02° in lead-lag angle for the next tests.

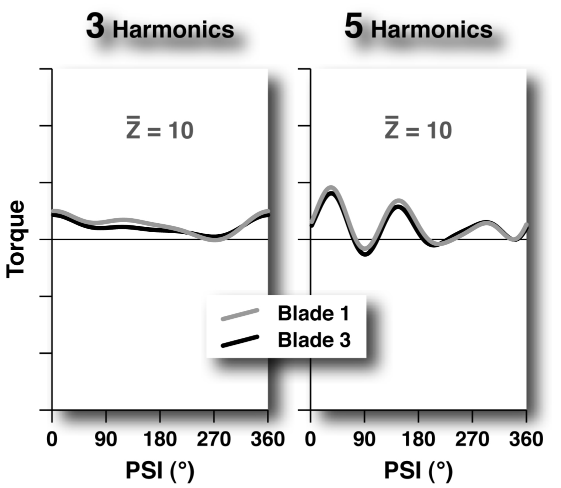

Fig. 13: Aerodynamic torque on a blade "Modane" control - Calculations up to 3rd and 5th harmonic

Pitch control influence on aerodynamic torque provided to one blade was evaluated with 3 harmonic results, which are considered as more secured. Results of test points performed with the same advance ratio, same drag and same lift coefficient but with "no flapping" and "Modane" pitch controls are compared in figure 14. These results tend to demonstrate that areas of low aerodynamic consumption are different. They are located around 100° in "no flapping" pitch control and around 280° in "Modane" pitch control.

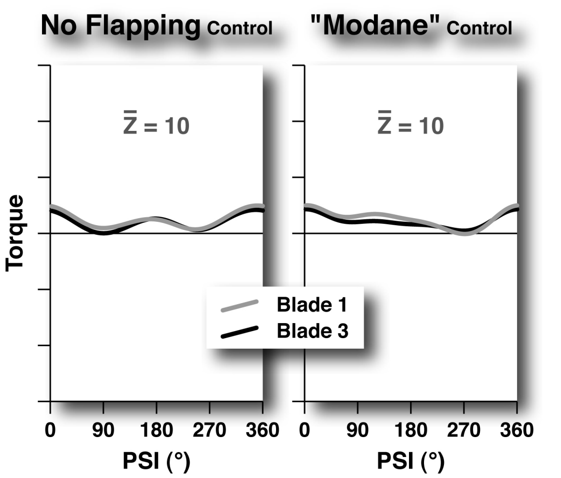

Fig. 14: Aerodynamic torque on a blade - No flapping / Modane pitch control

Only results, using a much bigger sample than is currently available, would enable these initial observations to be confirmed. Such a larger sample will be available next year.

However, with 3rd harmonic results, area of low and high aerodynamic consumption are already better known which will improve the blade geometry optimization from a performance point of view.

Dynamic loading at rotor center

After aerodynamic torque provided to one blade, results obtained by the analytical method for dynamic forces at rotor center are reviewed below.

When aerodynamic and inertia loads applied blade per blade are added and transferred onto fixed axes, dynamic forces generated by the blades at rotor center are obtained. This parameter is essential for helicopter improvements from a dynamic point of view. It's another great result of the analytical method and these calculations can be validated by comparisons with balance dynamic measurements corrected for inertia. This second method, described in the paragraph "Measuring Techniques", is based on the correction of the balance unsteady measurements by inertia terms.

Figures 15 and 16 show the balance loads before and after inertia corrections in the lift and drag axes. The loads after inertia corrections represent the rotor dynamic loading as determined by this second method.

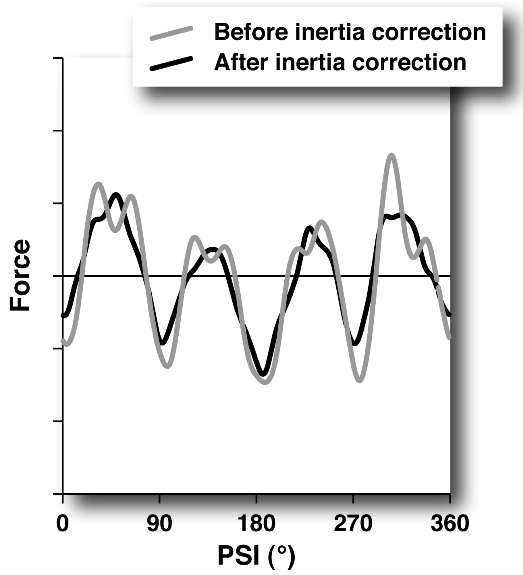

Fig. 15: Dynamic loading - Rotor lift loads before and after corrections for inertia

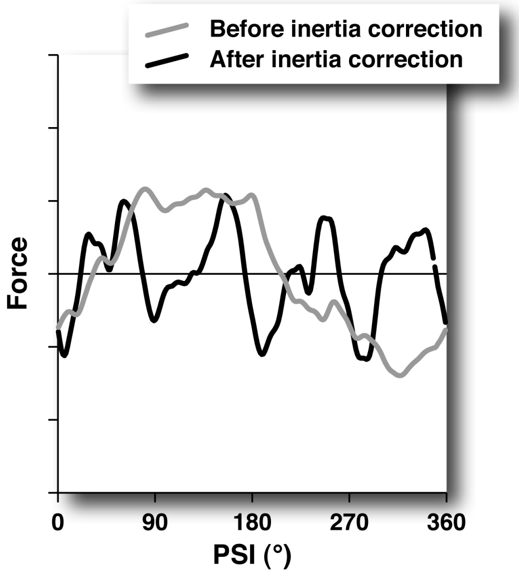

Fig. 16: Dynamic loading - Rotor drag loads before and after corrections for inertia

In figure 15, the inertia corrections in lift direction are weak because the hub is relatively rigid vertically. On the other hand, in figure 16, the inertia corrections in drag direction are important since the test point shown corresponds to a hub rotation frequency close to the natural frequency of the helicopter rotor test bench in X direction. The 4 per rev component, invisible before inertia corrections due to the natural frequency of the bench, becomes very significant in the corrected curve, which is to be expected from the theory.

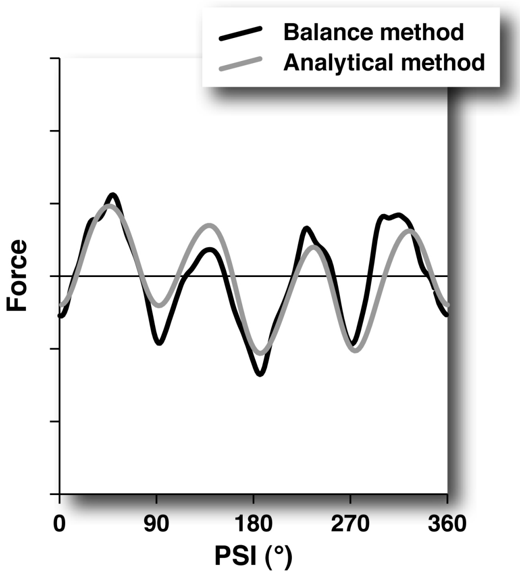

Fig. 17: Dynamic loading - Lift loads – Analytical method / balance corrected for inertia

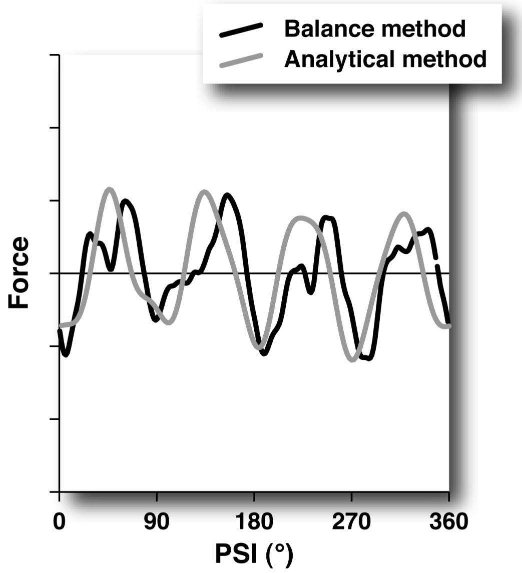

Fig. 18: Dynamic loading – Rotor drag loads – Analytical method / balance corrected for inertia

Figures 17 and 18 show the comparisons in the lift and drag axes between the analytical method and the method using the balance corrected for inertia loads. For both directions, the agreement is very satisfactory demonstrating that the two methods are valid for gaining access to the dynamic loading at rotor center.

It is very important to outline that the two methods are totally independent. Balance method involves balance measurements corrected for S4 and S5 inertia while analytical method uses blade pitch, flapping and lead-lag angles and S1.i, S2.i and S3.i inertia.

The analytical method however has the advantage of relying on relatively simple measurements (position of blade angles) whereas the balance method is dependant on measuring the flexibility of the different parts of the hub – an exercise not to be underestimated given the geometrical complexity of the hub. In addition the analytical method gives more detailed local information. For example only the dynamic loading at rotor center are presented in this paper and are accessible by the balance method. On another hand all the aerodynamic and inertia loads of each blade in relation to azimuth can be provided by the analytical method.

Conclusions and next steps

Equations using the relationship of the Dynamics and theorem of kinetic moment for the blades, pitch arms, lead-lag pins, hub rotating and fixed parts have been carried out, taking into account all the degrees of freedom between these systems, all the forces and whatever their inertia characteristics and center of gravity locations. The equilibrium equations that result are extremely complex, but on the other hand, the number of simplifying assumptions is greatly reduced in relation to what is commonly considered acceptable in publications.

Using this analytical method, essential parameters for rotor optimization such as aerodynamic torque generated by a blade during its rotation and the dynamic loading at rotor center can be calculated.

The application of this method, to an existing ONERA database, has enable already to:

- Show the good correlation between the rotor torque measured by the torque meter and calculated by the analytical method;
- Identify the azimuth zones corresponding to low aerodynamic blade torque, taking into account 3rd harmonic. This partly concurs with calculations performed by the ONERA Applied Aerodynamic Department (Ref 4) and will be used for blade optimization from a performance point of view;
- Reveal the important variations in aerodynamic torque when 5th harmonics are taken into account;
- Calculate the dynamic loading at rotor center;
- Bring to light the very satisfactory correlation between the dynamic loading obtained by the analytical method on the one hand, and that calculated by a method based on balance measurements corrected for inertia loads.

The analytical method has the advantage to use simple measurements which are blade angles while the balance method dependants on hub flexibility which is quite complex. Furthermore, while balance method provide dynamic forces at rotor center only, analytical method gives more detailed information since it provides dynamic forces (aerodynamic and inertia) blade per blade.

Development of the MACFAIR analytical method will continue by the introduction of blade deformations inside the calculations. These blade deformations will be obtained by a Strain Patern Analysis mastered by the ONERA Dynamic Department DDSS.

Comparisons between computed and measured rotor torque will be done for a larger number of test points to be acquired in 2004.

To improve the accuracy of the method, all the inertias and positions of center of gravity will be rigorously calculated due to the transfer of all of the hub plans using CATIA software. In addition the four blades will be equipped with measuring sensors for pitch, flapping and lead-lag angles with increased sensitivities. The feasibility of installing accelerometers to measure the angular lead-lag accelerations directly will be studied.

The method to determine dynamic loading at rotor center using the balance measurements will also be improved by increasing the knowledge of the flexible parts of the hub.

Programming of the analytical method will be carried out on the windtunnel computers in order to do real time calculations in future tests of all the values presented in this paper. On-line availability of these results will have the following two advantages:

- Enable continuous checking of the behavior of all the sensors used for input data with the analytical method. This checking is vital since misfunctioning of any one sensor strongly decrease the accuracy of the analytical method;
- Enable ONERA S1 Modane client to conduct its test program matrix in real time, using not only balance global results as in the past, but also individual blade results.

References

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