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VALIDATION OF ROTOR/HUB LOAD SYNTHESIS TECHNIQUES

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Abstract: The vibration of helicopters is due to the non-symmetrical aerodynamic loading of rotors in advancing flight. This loading coupled with the cyclic symmetry of the rotor results in a fuselage excitation mainly at the number of blades times the rotor rotation frequency. At this high frequency, the fuselage is flexible, which completely modifies the hub dynamic loading. It is naturally very important for a manufacturer to be able to predict the fuselage vibrations. This task is done with a comprehensive rotor code, but this is a difficult topic and much experimental validation is needed.

Direct measurement of hub loads in flight is difficult and expensive and so the objective of the work described in this paper is to try to infer ideal rotor dynamic hub loads from real rotor measurements such as blade bending moments. Several methods are presented and tested.
Using a Numerical Wind Tunnel experiment, it was first shown that such methods could indeed lead to a useful approximation of the expected dynamic hub loads.
Application of the methods to two available wind tunnel databases (DAT1 and 7AD1) was then performed. This provided interesting estimations of the expected experimental 6 component dynamic hub loads necessary to validate codes. As it has hardly been possible to check different methods on the same test case, further work is needed to complete the study.

INTRODUCTION

The vibration of helicopters is due to the non-symmetrical aerodynamic loading of rotors in advancing flight. This coupled with the cyclic symmetry of the rotor results in a fuselage excitation mainly at the number of blades times the rotor rotation frequency. At this high frequency, the fuselage is flexible, which completely modifies the hub dynamic loading.
It is naturally very important for a manufacturer to be able to predict the fuselage vibrations. This task is usually undertaken with a comprehensive rotor code, but this is a difficult topic and much experimental validation is needed.

Unfortunately, validating the dynamic hub loads induced by an experimental isolated rotor is problematic. At the frequencies involved at model scale, the wind tunnel rig is also flexible and movement of the hub distorts the classical rotor hub force measurement. Several methods exist for inferring hub loads from rotor measurements and the object of this paper is to assess their accuracy and to provide advice for conducting dynamic hub load measurements.

1 PRESENTATION OF THE DATABASES

Dynamic hub loads will be analysed with the help of the following databases:

1.1 The Modane 7AD1 database

The 7AD1 database was measured in the mid 90s in order to validate the existing helicopter codes. The 7A rotor is 4 bladed, articulated, and equipped with rectangular blades. The blades are made up of two airfoils: OA213 from the root to 75% of span and OA209 from 90% of span to the tip. Between these two limits the airfoil are interpolated linearly.
Several blade tips were tested in addition to the reference rectangular planform. The 7AD1 blade refers to a parabolic tip with anhedral angle.
The rotor was extensively instrumented, mainly with:

- 20 pressure transducers on upper and lower surfaces along 5 blade sections,
- 6 blade strain gauges in flapping and lead-lag and 2 in torsion calibrated in Nm,
- 4 mast strain gauges (bending in the rotating frame),
- 25 blade strain gauges dedicated to blade deflection measurement by a Strain Pattern Analysis (SPA) method and calibrated on a blade mode set,
- A 6 dof balance recording hub loads.

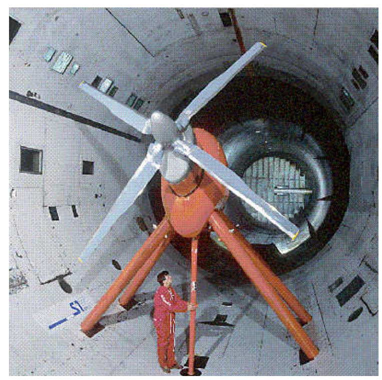

Figure 1 – The Modane test rig and its 90^o pitch attitude capabilities (blades of the 7DA1 blades size)

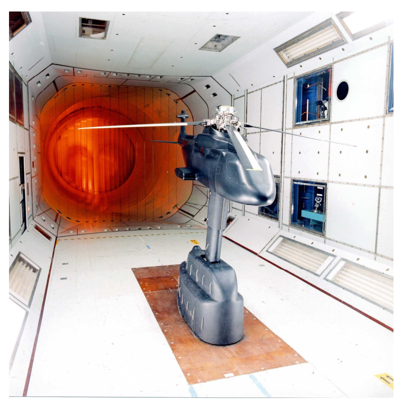

Figure 2 – Lateral QinetiQ rotor rig with DAT1 blades and fuselage model in 5m Wind Tunnel)

1.2 The DAT1 database

The DAT1 blade set was produced over 8 years ago as a baseline rotor blade to be used as a comparator to research blades exploring concepts of aeroelastic tailoring and structural optimisation. As such this blade has dynamic characteristics typical of existing helicopters and so is an ideal blade for the purposes of this study.

The database, made available by QinetiQ and the UK MOD for the GARTEUR programme, consists of the DAT1 blade set both with and without a fuselage. The rotor rig used for the DAT1 test is shown in Figure 2 with a fuselage attachment.

The DAT1 composite blade has a rectangular planform with 9 strain gauge stations each measuring flap, lag and torsion moments on the master blade and a reduced level of instrumentation on the other blades Pitch link loads, flap and lag angular displacements and hub accelerations are also measured as well as the hub fixed frame forces and moments obtained from a hub balance. The rotor is equipped with a balance mounted in the rotating frame dedicated to dynamic hub load measurements.

1.3 A small Numerical Wind Tunnel test

A small numerical wind tunnel was constructed using the ROTOR comprehensive code (Ref. [7]). The aim is to test numerically the validity of the dynamic hub load synthesis technique. This exercise assumes that the calculated aerodynamic efforts are correctly integrated along the blade and that the dynamic blade model also behaves reasonably well so that representative hub loads are generated. Aerodynamics need not be accurate. A Meijer-Drees induced velocity model is used together with an airfoil dynamic stall model.

This model can be run at will with a flexible rig representative of a real wind tunnel test, or with a rigid rig leading then to the ideal measurement to be inferred.

The tested rotor is a model of the 7AD1 Modane rotor and the rig is a structure made of 6 articulated masses that are chosen so as to reproduce the masses and frequencies of the real Modane rig. Despite this model being crude and non-optimized – it lacks a body mode under the 4/rev frequency – it has been shown to reproduce the abnormal behaviour of a real balance.

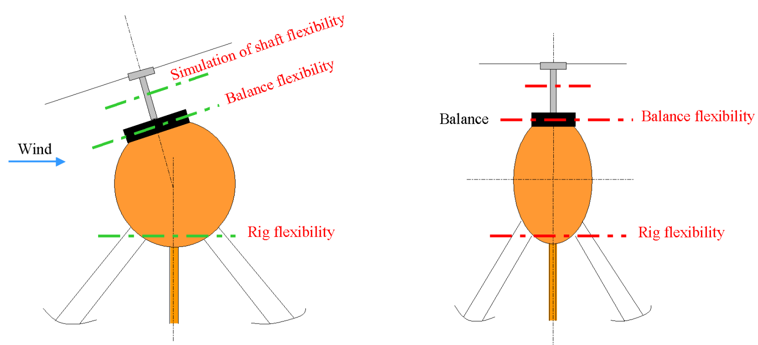

Figure 3 – Lateral and longitudinal view of the Modane rig and the 6 chosen hinges of the model

1.4 General presentation of the results

Hub loads sign convention is positive upward, forward and to the pilot left.

All of this study is centred on 4 bladed rotors and results are concentrated on the predominant 4/rev hub load. The forces and moments will be presented on the complex plane for various advance ratios at constant rotor loading, as on Figure 4.

- DAT1 results are presented between μ=0.1 and 0.35 at $Ct/\sigma = 0.08$,
- 7AD1 rotor and the numerical experiment between μ=0.284 and 0.465 at $Ct/\sigma = 0.0625$,

Each time, a black dot will show the lowest advance ratio and a red one the largest.

2 ROTOR HEAD STRAIN GAUGE MEASUREMENTS

2.1 Principle

Strain gauges are implemented at the rotor head, in the fixed frame at the top of the rig or in the rotating frame on the shaft. The fixed frame configuration does not give access to the rotor torque. For the rotating frame configuration, recombination of signals and harmonics has to be performed.

2.2 Influence of hub vibrations

Strain gauges correctly measure the unsteady loads at the rotor hub but if the rig is not rigid, which is always the case, it also measures the inertial loading induced by the vibration.

A test performed on the Numerical Wind Tunnel shows the amplitude of the distortion on a realistic case (Figure 4). If the 4/rev vertical load is not too affected, the longitudinal component sees a whole change of sign.

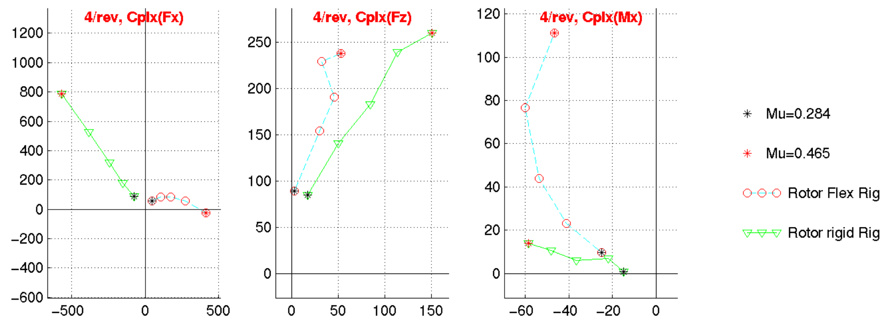

Figure 4 – Numerical wind tunnel: Effect of rig vibration on hub loads.
Longitudinal load (left), vertical load (centre) and roll moment (right)

2.3 Acceleration correction

A remedy to this problem is to measure the hub acceleration and subtract the inertial load of the rotor. Blade flexibility and movements are ignored. Figure 5 shows what could be gained from this correction on the numerical wind tunnel. Longitudinal load is well approximated (20% underestimation) but no correction is achieved on moments or on the vertical force (there were no acceleration on these components). It is to be said that this test is too ideal since the rotor hub is represented by a point mass in the model.
Although the hub acceleration may not be easy to measure accurately, this correction is the minimum to be done to take advantage of balance measurements in the absence of dynamic calibration.

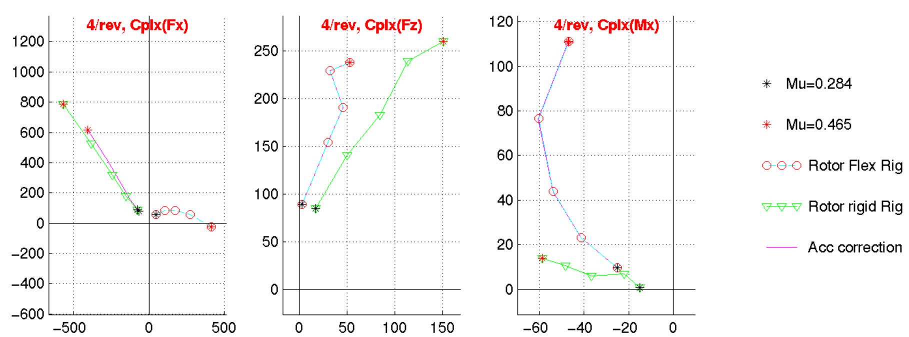

Figure 5 – Numerical experiment: Getting rigid rig loads (green) from flexible rig measurements (cyan)
Longitudinal load (left), vertical load (centre) and roll moment (right)
Effect of acceleration correction on strain gauges

2.4 Dynamic calibration

A classical way to account for the rig movement is to measure the gauge signal coming from calibrated excitations at the hub centre at the frequency of interest and build a transfer matrix. This transfer matrix is then used to estimate the hub loads. Calibration is a term usually synonym of the best measurement accuracy. Here, this method cannot yield the expected rigid rig dynamic loads since the vibration itself modifies the aerodynamic loading.

Balance calibration is practically done by replacing the blades by dummy masses and with no rotor rotation. Under these conditions, the Numerical Experiment helped to check the accuracy of the procedure. Additional numerical tests were also performed with different dummy masses, with the real blades, with and without rotation and accounting for the rotor pitch attitude. A set of main results are displayed at Figure 6. The main conclusions that could be drawn are:

- Accounting for the pitch attitude did not improve the predictions for this particular test,
- With dummy masses, the use of the classical half blade mass value leads to the best results when looking at the 6 components,
- Dynamic calibration with rotor rotation improves the moments (it account for gyroscopic effects),
- Only by calibrating with the real rotating blades can one achieve quantitative measurements.

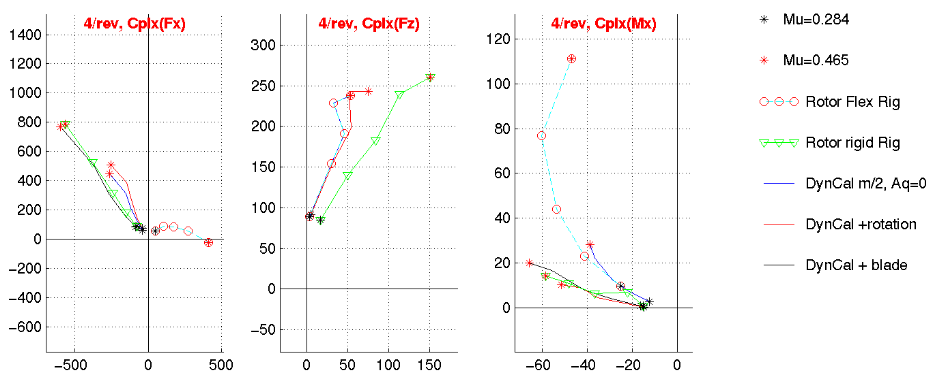

Figure 6 – Numerical experiment: Getting rigid rig loads (green) from flexible rig measurements (cyan)
Longitudinal load (left), vertical load (centre) and roll moment (right)
Calibration with classical dummy masses of half blade mass at rest (blue), with rotor rotation (red) then with the real blades in rotation (black).

In final, the results obtained here are quite positive for this method. Efforts should be done so as to calibrate with the real blades, which could be performed by putting the blade at very low thrust so as for them to work in a clean aerodynamic environment and do not induce too much wind around the rig.
The presence of rig modes in the vicinity of the 4/rev frequency will add a lot of scatter to the method predictions which this ideal test will not show.

3 AERODYNAMICS DEDUCED FROM BLADE POSITION (CROZIER)

3.1 Principle

During wind tunnel tests, the blade root movement of articulated rotors is carefully measured. Reference [3] proposes to use the known blade flapping and lead-lag angles to calculate the

necessary aerodynamic moments needed to create this movement, assuming that the blade is rigid. This requires the hinge stiffness to be well characterized.
Blade moments at the root are not sufficient to determine the blade aerodynamics well enough. Reference [3] assumes that these moments are produced by a force applied at a specific point on the blade which is named the radial aerodynamic centre. This point is taken at 70% of the rotor radius and at the section first quarter chord. Once this radial aerodynamic centre is chosen, loads at the hub centre, including rotor torque, are determined.

3.2 Results

The Crozier method was applied using a distributed aerodynamic loading $F = F_0 \cdot r^{4/3}$ chosen so that its aerodynamic centre was located at 70%R.
The numerical experiment shows (Figure 7) that the method reproduces the phase but overestimates the amplitude of the loads. This is because with rigid blades and the given hinge angles, the generated centrifugal moment is too large and has to be balanced by too large aerodynamic loads. It would thus be interesting to find a way to account for the blade bending.
On the other hand, 4/rev torque is well reproduced because the rigid blade assumption is more valid in lead-lag.

3.3 Soft blade investigation (not an experimental method)

The Crozier analysis was performed here by setting on the blade dynamics option of the ROTOR code work. The improvement is significant as seen on Figure 7. This at least shows that the blade flexibility should rather not be neglected.
This local test is interesting and highlights the issues involved but cannot be considered as a new dynamic hub load inferring method since it relies upon a comprehensive code dynamics analysis and the aim of this work is to validate such codes

3.4 Soft blade extension (an experimental method)

As it appears that improved results may be obtained if the blade were assigned its true position, a check was made using the first cantilevered blade flapping mode imposed with the measured curvature at a given section (30%R was chosen). The required additional force used to dynamically balance the rotor was a simple constant radial lift distribution.
Figure 7 shows that the dynamic loads are better inferred, however, there is still room for improvements. Although a second gauge would help to provide a better approximation, there is still the possibility the technique may run into ill-conditioning with small curvature errors inducing large loads.

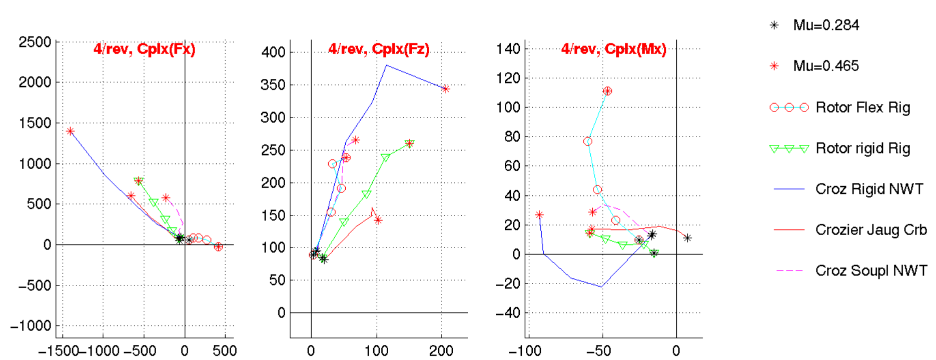

Figure 7 – Numerical experiment: Getting rigid rig loads (green) from flexible rig measurements (cyan)
Longitudinal load (left), vertical load (centre) and roll moment (right)
Crozier method (blue), Crozier soft blade extension method (red)
and Crozier analysis run with blade dynamics (Soft blade investigation, dotted)

3.5 Conclusions

The Crozier method uses the simple flapping and lead-lag angles to evaluate the 4/rev hub loads. It generally overestimates the load amplitude but produces correct phases. Extending the method to account for some blade flexibility seems promising but more developments are needed to fully assess this option.

4 HUB LOADS INFERRED FROM STRAIN GAUGE DATA FITTING

This family of method uses blade strain gauge information to infer hub loads. A version has been developed at QinetiQ (MSM) and at ONERA (SPA).
Issues with these methods are described through an application to the DAT1 strain gauge records and to a simulation of a rotor on a large finite element blade model.

The use of these methods relies upon the hypothesis that rig vibration does not influence much blade moments. Figure 8 obtained with the numerical wind tunnel in the same conditions as Figure 4 shows that a certain amount of uncertainty cannot be avoided.

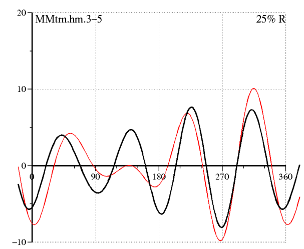

Figure 8 – Numerical wind tunnel, lead-lag blade moment at 25%R Harmonics 3 to 5 Rigid rig (Red) Flexible rig (Black)

4.1 Application to the DAT1 strain gauge records

The Modal Summation Method (MSM)

The Modal Summation Method (MSM) is a method for generating the hub and blade loads using the measured strain data along the blade. The method was developed at QinetiQ and employs a least square fitting technique using hub-fixed blade modes as the degrees of freedom. The blade modes are calculated using a QinetiQ in-house modes analysis program which generates the modal bending moments in each mode. The modal bending moments are then used in conjunction with a standard NAG routine to solve the matrix solution Ax = b where A is a rectangular matrix of size m x n. The number of gauges, Ng, is normally higher than the number of blade modes, Nm, hence the use of a solution based on the least-square method.
In order to deal with the null moments of the first flapping mode, the flapping angle – the "strain" at the blade root - is used as a supernumerary gauge.

$$\underbrace{[M]}_{\substack{\text{Modal Moment}@(r)\\(Ng\times Nm)}} \cdot \underbrace{\{\phi\}}_{\substack{\text{Modal displacement}\\(Nm\times 1)}} = \underbrace{\{m\}}_{\substack{\text{Measured Moment}\\(Ng\times 1)}} \quad (1)$$

The modal displacements which are a function of azimuth angle, ψ, are then used to reconstruct the loads using the modal summation method:

$$\sum_{i=1}^{N_m} M_i(r)\phi_i(\psi) = M(r,\psi) \quad (2)$$

The technique is applied to all three components of blade loads, i.e. flatwise, edgewise and torsion moments. Only the blade outboard of the root cut out are normally strain-gauged and the centre-line hub loads are deduced from the blade loads at the root with contributions from any external load paths, such as pitch change mechanism taken into account. The method is further expanded to perform harmonic analysis of the modal bending moments to provide a useful diagnosis of the blade loads and their origin.

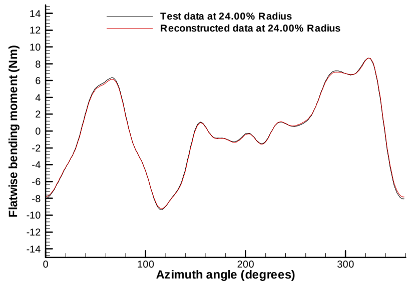

Figure 9 – Flatwise blade Moment fitting by the MSM technique (24% radius).

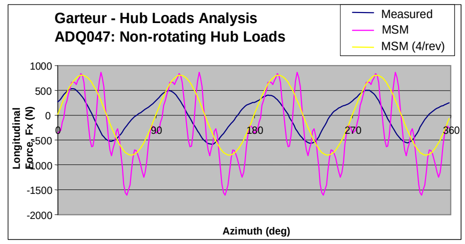

Figure 10 – Longitudinal dynamic hub load inferred by the MSM technique μ=0.20 and C_T/σ=0.08 . "Measured" stands for balance signal and is not a reference.

Results

The MSM reconstruction of the test data at each azimuth is generally good as can be seen on Figure 9. Modal superposition leads to the desired dynamic hub loads. Uncertainties are responsible for too high an harmonic (Figure 10) content which ought to be filtered so that the highest frequency retained is comparable to that of the mode with the highest frequency used.
However there are still some anomalies that need to be investigated with the method in reconstructing the non-rotating hub loads.

4.2 Application to a finite element simulated rotor

The Strain Pattern Analysis method

The Strain Pattern Analysis (SPA) method (Ref [4]) is used at ONERA to measure the hub vertical load. It follows the same principles as the MSM technique and makes use of calculated rotating modes as blade deformation basis. For convenience, the set of gauges stuck on the blade are calibrated on experimental articulated modes and a transfer between the experimental non rotating basis and the rotating one is to be calculated.
WB Bousman (Ref [2]) made an extension of this method that gives access to the whole blade vertical aerodynamic loading, based on the fact that the use of the blade rotating modes simplifies the equations so that the blade loading kth harmonics all along the blade can directly be written as:

$$F_k(r) = \sum_{i=1}^{n} (\omega_i^2 - k^2\Omega^2) \cdot \mu(r) \cdot \lambda_{ik}(t) \cdot \Phi_i(r) \quad (3)$$

in which ω_i is the ith mode frequency, μ(r) the blade mass repartition, λ_{ik} the kth harmonics of the ith mode participation and Φ_i (r) the ith mode displacement. This property may give access to additional experimental stuff.

Application to a finite element rotor model

In the frame of this study, a special test of the SPA method was attempted using a finite element model of a real blade in order to simulate the analysis on real blades and identify unexpected problems.
The chosen blade is feathered over 25% of the radius. The work makes use of the MARC finite element program which calculated the skin strain of the blade rotating modes at several gauge locations and also time integrated the model until a periodic response was obtained using a technique developed by K Truong (aerodynamics is accounted for and provides the necessary damping). SPA analysis was then performed in order to infer the hub dynamic vertical load and compare it to the value calculated by the finite element code.

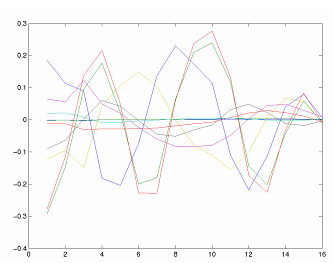

Figure 11 – Blade flapping strain for the first 10 blade modes versus number of gauge

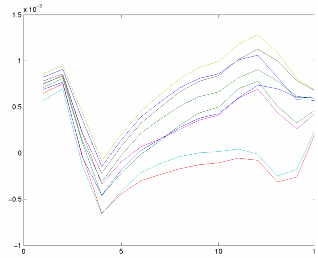

Figure 12 – Blade flapping strain for 9 azimuths in forward flight versus number of gauge

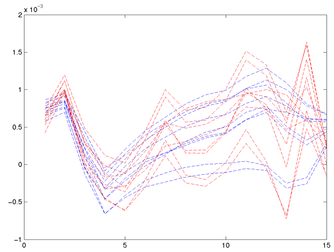

Figure 13 –Blade flapping strain for 9 azimuths in forward flight versus number of gauge (blue) and its fitted value (red)

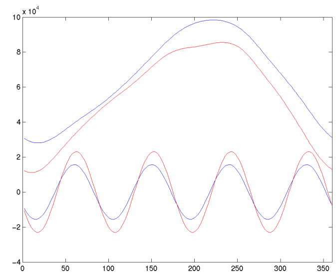

Figure 14 –Actual (blue) and inferred (red) vertical hub load (blue). The curves below are the extracted 4^{th} harmonics (magnified 20x).

Many unexpected difficulties were encountered during this test. The strain gauge type strains were difficult to extract from the huge finite element output and these outputs were different for the modes and the time integrated response.

In the end, the modal gauge signals were found to be quite continuous versus radius (Figure 11) while the aerodynamically loaded blade shows a definite strain discontinuity at the onset of the feathered sections (Figure 12). Curve fitting on the feathered part of the blade only leads to nice fittings but wrong blade position. Conversely, curve fitting on all the gauges is poor (Figure 14) but a better agreement is found on the final vertical load which are reproduced with an error of about 20%. The non feathered part of the blade plays an important role in the hub vibratory loads.

The aim to obtain the whole rotor behaviour - blade deformation and aerodynamics - through Eq (3) could not be achieved. Completing the modal base by static blade deformations to known loads might lead to a better conditioned problem.

4.3 Conclusion

If one has access to a good blade model, modal strain gauge fitting can be a very useful technique for generating the hub loads from measured strain gauge data as blade strain is not affected too much by the rig vibration.

The MSM tested method can provide a good fit to the flap, lag and torsional components providing that measurements are made at a sufficient number of radial stations, including on the non feathered part of the blade. Filtering out the high frequency content of the measurements is essential to avoid high frequency harmonics in the reconstructed data as the least squares fitting method attempts to model noise.

The aim to obtain more information by SPA (aerodynamic loading) could not be achieved on a real blade application.

5 COMPREHENSIVE CODE GAUGE/HUB LOADS CORRELATION (COSTES)

5.1 Principle

The idea is to search for a correlation between blade strain and hub loads using a helicopter comprehensive code and a set of flying conditions. Once this correlation is established, it is applied to the experimental blade strains and leads to approximated hub loads.

Technically, if F_k is one hub load component for the flying condition k, one writes:

$$F_k(t) = \sum_{g=1}^{N_{Gauges}} a_g \sigma_{gk}(t) \qquad (4)$$

This equation has N_G (number of gauges) unknowns but has to be written for the N_{AZ} available azimuths and the N_{FL} flights. The total number of equation is $N_{AZ}.N_{FL}$ and the solution of the system is chosen by a least square method.

In practice, adaptation to this simple scheme has to be done:

- Blade flapping angle has to be taken into account in addition to the blade strain, since flapping is important for the hub loads whilst it induces no signal to the strain gauges,
- First and second derivatives of blade measurements (strains and flapping) are also used as inputs,
- For N_{Blades}/rev hub loads, the time discretisation and the derivatives are simplified into the sine and cosine components in N_{Blades}/rev.

5.2 Results

This method sometimes yields satisfactory loads, and this was the case for the 7AD1 experiment. But some components are not correctly predicted as can be seen on the Numerical experiment Figure 15. This method is judged not to be reliable enough to be used.

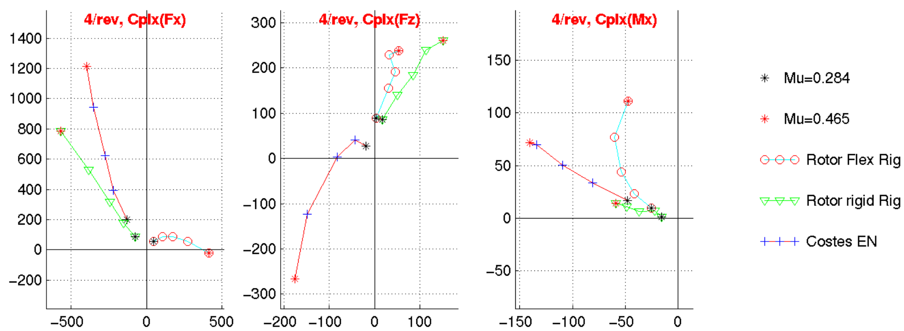

Figure 15 – Numerical experiment: Inferring rigid rig loads (green) from flexible rig measurements (cyan)
Longitudinal load (left), vertical load (centre) and roll moment (right)
Loads inferred from comprehensive code gauge/hub load correlation.
Results are much unsatisfactory on the vertical load.

6 APPLICATIONS

6.1 Application to the DAT1 database

Several difficulties were encountered with the DAT1 database. A clean rotor aerodynamic configuration could be obtained only for the isolated rotor and unfortunately a complete rotating balance dynamic calibration was not available.

However, the 5x5 hub transfer function was measured and the difficulties due to the presence of a rig mode too close to the 4/rev were identified. Such frequency coalescence is to be avoided if at all possible.

On this database, the vertical load/vertical excitation transfer function is unity due to the vertical stiffness of the rig. It could also be seen that at 4/rev an anti-resonance (or trough) is present in the response curve which indicates a lack of balance acceleration at this frequency due to a side force. This should imply a faithful reproduction of hub forces in the vertical and side

directions by the balance - there may however be some influence from the cross terms due to other force and moment components.
These two components of the inferred loads are thus presented at Figure 16 together with the balance raw output.

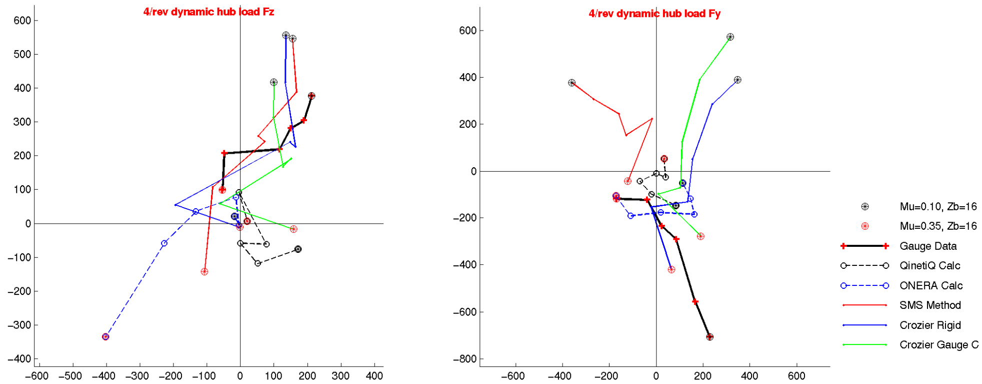

Figure 16 – DAT1 vertical (left) and lateral (right) 4/rev hub loads.
Non calibrated balance (black), inferred (solid lines) and calculated (dotted).

It can be seen that the MSM and the Crozier predictions behave similarly to the directly measured balance loads for the vertical component. For the lateral load, the Crozier and MSM loads have a 60^o phase difference and comparable amplitudes. Meanwhile, the balance measurement lies at almost the opposite sign.
The overall results are not yet clear enough. Many small experimental problems have limited the output of the DAT1 experiment which was so well suited to this study. It is hoped that additional testing can be performed.

Figure 16 results also show the loads predicted by QinetiQ (code CRFM with prescribed wake, ref [6]) and ONERA (ROTOR code with prescribed wake, ref [7]). The scatter emphasizes the need for achieving a better estimation of these important 4/rev hub loads.

6.2 Application to the Modane 7AD1 database

Dynamic hub loads were estimated on the Modane 7AD1 test using mainly the Crozier method. Just as for the DAT1 test, the vertical component given by the inferring method is confirmed by the balance. On this component, the SPA analysis especially wired for this test does not give satisfactory results (always measuring 40% of the expected amplitude), a fact which has motivated a special study of this method.
The Crozier method and its different options to account for the blade flexibility finally gave a coherent idea of the 7AD1 dynamic hub loads in amplitude and phase. However, just as for the DAT1 experiment, really conclusive tests would have consisted in obtaining analogous loads from several independent methods.

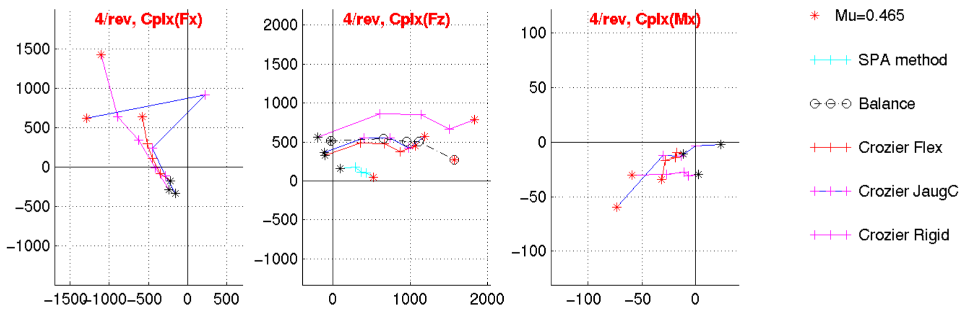

Figure 17 – 7AD1 4/rev longitudinal (left) and vertical (center) hub loads, roll hub moment (right). Inferred dynamic loads.

As for the DAT1 database, the prediction of the 4/rev hub load differs widely between the partners and thus reliable experimental loads would be of great interest. The code used were ROTOR (ONERA, prescribed wake model and wall correction, ref [7]), CRFM (QinetiQ, prescribed wake model, ref [6]), and FLIGHTLAB (NLR free wake model, Ref [9]).
Results with ROTOR and the use of a wall correction seems to follow the 3 hub load components given by the tested inferring method but confirmation is needed as this may be fortuitous.

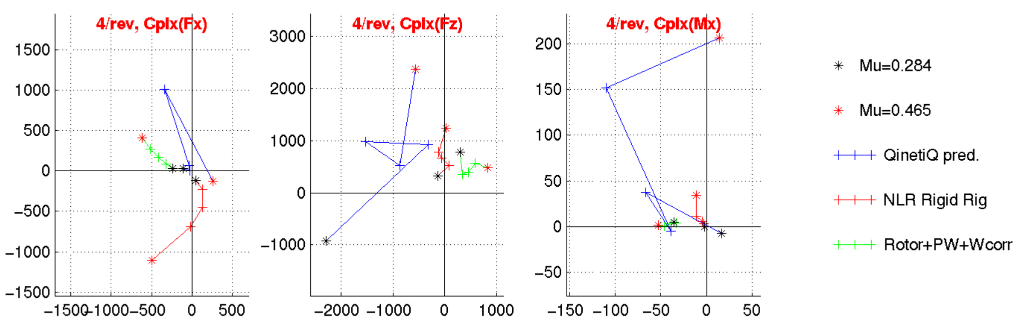

Figure 18 – 7AD1 4/rev longitudinal (left) and vertical (center) hub loads, roll hub moment (right) Predictions by the partners.

7 CONCLUSIONS

Several methods for inferring the hub dynamic loads from classical wind tunnel measurements were evaluated. The main conclusions that could be drawn are:
-- The rig must not have a frequency too close to N_{Blade}/rev frequency which would increase the uncertainties especially with balance calibration,
--All the methods provide only approximations of the hub loads when the rig vibrates,
-- Dynamic calibrations with dummy masses do yield valuable results but to obtaining the best results, the calibration should be performed with the actual rotating blades, which unfortunately is not very practical,
-- Strain gauge modal calibration necessitates a blade well equipped with strain gauges, especially on the non feathered sections, as well as a good blade dynamic model. It should then yield a good approximation of the desired loads,

-- The Crozier method with rigid blades gives an approximation of the loads in the absence of a blade model and strain gauges. Extension to account for blade flexibility was attempted, but further work is still needed.

Approximations of the 6 component hub dynamic load could effectively be obtained on both databases, with reasonable consistency for some components. Unfortunately, firm conclusions could not really be drawn because several experimental difficulties made the systematic comparison between load inferring methods not possible.
Additional testing and data comparisons remain necessary.

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