

## DYNAMICS STUDIES OF THE ERATO BLADE, BASED ON FINITE ELEMENT ANALYSIS

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**Abstract:** This report concern is about dynamic studies of the ERATO (a French acronym for “Etude d’un Rotor Aéroacoustique Technologiquement Optimisé”) blade, based on Finite Element FE analysis. This aeroacoustic optimized blade is characterized by a planform shape deviating largely from the classical rectangular one. Studies are directed towards the goal of coupling CSM (Computational Structural Mechanics) methods with CFD (Computational Fluid Dynamics) ones. The first step has been the establishment of an engineering approach for elaborating a 3D FE model, sufficiently realistic but with no heavy demands in computation time. The numerical tools are the commercial codes MSC/Patran for meshing and MSC/Marc for calculations, the latter code having been thoroughly tested for cases representative of the helicopter rotor blade. The 3D FE model, elaborated with less than 10000 nodes, is validated against modal measurements of the blade clamped at its root and those of the blade suspended at a ceiling. The correlation of the predictions of the 3D FE model with the experimental results is satisfactory, given the numerous uncertainties in materials’ properties, blade fabrication, experiments and accuracy of predictions of the structural code. It provides better results than the (1D+2D) FE model. Furthermore, the model predicts for the blade rotating at a speed  $\Omega$ , an important component of the torsion deflection at the frequency near  $5 \Omega$ , coming from the flap-torsion fifth mode. Such feature is not well taken into account by the (1D+2D) model and is in agreement with experimental results.

### Introduction

The main rotor blade of helicopters has usually rectangular planform shapes, with eventually a small portion of the blade tip deviating from the rectangular shape. Designing special blades with more exotic planform shapes requires important efforts involving elaborate aerodynamic and dynamic studies. However, such task can be rewarding, an example is provided by the BERP blade which has set a speed record. Another example of advanced geometric shape is the ERATO blade (a French acronym for “Etude d’un Rotor Aéroacoustique Technologiquement Optimisé”), fruit of a collaboration between DLR and ONERA. This blade was designed during the

years 1992-1998 for a better aeroacoustic behavior: indeed, it permits a noise reduction of 4 to 7 dB in descent flight, depending upon flight conditions [Ref. 1]. It has a planform shape that deviates largely from the classical rectangular one (cf. Fig.1), such feature leads to a dynamic behavior that escapes the prediction of the aeroelastic code used in the 1990’s, the code R85 of Eurocopter. The blade has been modeled as a beam with its mechanical properties deduced from sectional characterization, according to the classical (1D+2D) FE analysis for the helicopter rotor blade. For the ERATO blade, it is then suspected that such analysis isn’t valid and a 3D FE analysis would be more appropriate.

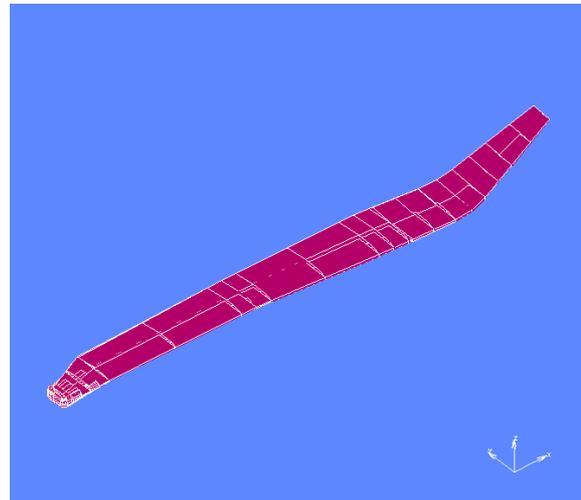


Fig.1.- External shape of the ERATO blade

Applying advanced CSM Computational Structural Mechanics to the rotor blade requires solving the two following problems: elaboration of a 3D FE model of the rotor blade and making FE analysis. The helicopter blade has a slender shape, its thickness is very small compared to the blade chord and the blade span. Such geometric particularity leads to a very high number of nodes for meshing the blade, a “good FE element” is subjected to have a ratio of its largest dimension over its smallest dimension less than 10. Moreover, since the final goal of this study is to couple CSM methods with CFD methods, a limitation of structural degrees of freedom is necessary for limiting computational time. The challenge for the

elaboration of a 3D FE model is to get a sufficiently realistic model with the number of nodes restricted to the minimum. This report will expose a new engineering procedure of meshing a helicopter rotor blade and its application to the ERATO blade.

The research undertaken up to now at ONERA is focused mainly on aerodynamic modeling, based on CFD techniques. Dynamics studies are limited to modeling based on 3D beams. To rapidly set up CSM studies, there is no other alternative than getting off-the-shell solutions, i.e. commercial codes. The MSC/Marc code has been chosen for its non linear capabilities and it has been thoroughly tested for cases representative of helicopter rotor blades. This choice leads to the selection of the MSC/Patran code for meshing, as these two codes are compatible.

### **Establishment of the 3D FE model**

#### **Objectives**

The goal is to obtain a realistic 3D FE model with economical CPU demands. For CFD approach, it is usual that the model involves millions of nodes. CSM models with such number of nodes would require high computational loads that are not manageable with middle-range powered workstations. From our FE analysis experience, it is estimated that the limit number is about 10000 nodes.

#### **Analysis of the modeling difficulties**

The difficulties for meshing a helicopter rotor blade come from its slender shape. Dimensions of elements for FE analysis are restricted to having a ratio of the largest dimension over the smallest dimension of less than 10. So the controlling dimension is the blade thickness at the trailing edge. The ERATO blade is elaborated for the purpose of research, so it is equipped with heavy instrumentation: strain and pressure sensors with their wiring, account nearly for 7 % of the blade weight [Ref 2,3]. For practical modeling purpose, only the electric wiring put along the torsion box of the blade is modeled, by using beam elements. As most advanced blades, the ERATO blade makes use of various multi-layer composite materials. The mechanical properties of these composites are not known accurately.

#### **Numerical tools**

CSM codes haven't receive many efforts of development at ONERA . To quickly start research studies, there is no other alternative than choosing commercial codes. The code selection is made according to the following requirements: capabilities of predicting nonlinear structural

behavior and possibilities of incorporating user subroutines. The MSC/Marc code has been selected accordingly. Furthermore, it has been tested thoroughly against various cases mirroring different dynamic aspects of helicopter rotor blade working environment: a rotating beam [Ref 4], multi-layer composites [Ref 5, 6] and deformations of a nonlinear beam subjected to point loads [Ref 7]. The test case of a rotating beam has permitted to detect the incorrect implementation of the Coriolis force in the MSC/Marc code and at our request, the development group of MSC has rectified it. The results obtained with the MSC/Marc on these test cases are satisfactory.

Our recent studies lead to some doubt about the accuracy of the predictions by the structural code of modal frequencies of curved multi-layer composites, when the composites are put at some offset distance from the FE nodal surface. For that purpose, a simple cylinder covered with multi-layer composites is considered. Two modal calculations are made on this mechanical system but with two different offset distances: in the first calculation, the nodal surface is put at the middle surface of the composite; in the second, it is put at the interior surface of the composite. The predicted modal frequencies should be identical for both calculations but are found different, particularly the torsion frequency. A request has been made to the development group of MSC in order to rectify this feature.

The choice of the MSC/Marc code leads naturally to the selection of the MSC/Patran code as meshing tool. The two codes have some tools for exchanging data files.

#### **Engineering approach for meshing**

For helicopter rotor blades, geometric and material lay-outs are given at various blade sections, these properties are used for calculating the beam mechanical properties. So, it is natural to divide the blade into various segments, each of them bounded by defined sections.

A preliminary work is done before meshing the whole blade. Some typical blade sections are chosen and used for elaborating different beams with a uniform section and an aspect ratio (length/chord) about 10. A meshing with a minimum number of nodes is searched for these beams, in order to get the best correlation between experimental and calculation results of mechanical properties. Experiments are based on the method of Poggendorf and provide the values of mechanical stiffness, but these results have to be taken with some caution as this method has been only validated for straight blades. Calculations have been done with various codes: the 2D code of the department of DMSE – ONERA [Ref 8], the MSC/Nastran code using a 3D FE model elaborated

by the same department [Ref 9] and the MSC/Marc code using the 3D FE model elaborated during this study. The two 3D FE models differ primarily by the number of elements: the DMSE FE model involves more elements than the present FE model. For instance, at the section of 713 mm from the rotor center, there are 80 elements in the first and 42 in the second. The mechanical properties predicted by the various methods described above are shown in Table 1 for the blade section at 713 mm. The MSC/Marc code predicts lower value of the flap stiffness than the MSC/Nastran code, like the DMSE code, but it predicts a better value for the torsion stiffness. Two other blade sections are studied, the results are not shown here, but the same conclusions can be held. To conclude this preliminary work, the procedure adopted here for limiting the number of elements appears to be justified.

Table 1.- Mechanical properties of the blade section at 713 mm from the rotor center (the experimental errors don't give the real bounds of uncertainties: see accompanying text)

	Exper- iments	MSC/ Nastran	DMSE code	MSC/ Marc
Flap stiffness (N.m <sup>2</sup> )	700±30	682	624	620
Lead-Lag stiffness	41000± 6000	—	33000	33400
Torsion stiffness	960±40	891	—	916

For meshing the whole blade, it is possible to start from the segment having one blade section studied during the preliminary work. For each segment, meshing is initiated from inboard and outboard surfaces, these meshes are not necessarily identical but must be homeomorphic, i.e. they can be deduced by geometric deformation: cf. Fig. 2. The volume meshing of the blade segment is obtained by an operation joining the two surface meshes (called "loft", according to the MSC/Patran code).

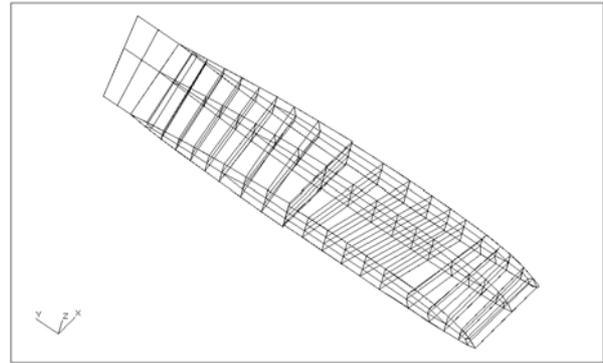


Fig.2.- Meshing of a blade segment

The meshing is then extended from the initial blade segment to the blade tip and to the root. For the latter extension, some simplifying approximation of the real structure is assumed using the fact that the blade root is much stiffer than the outboard blade: the two holes for the bolts are reduced to two points (cf. Fig. 3). The blade tip is constituted mainly of homogeneous material, with the absence of spar at a distance about 3 chords from the blade tip. For this reason, the meshing of the segments at the blade tip region doesn't need to be as fine as the inboard segments. Coarsening the meshing creates incongruent surfaces at the interface between fine and coarse meshes (according to the terminology of finite element analysis) : this can be remedied by tying the nodes in the fine meshing that are no more present in the coarse meshing to the neighboring nodes. So, by introducing such special links, it is possible to make coarse meshing for the segments near the blade tip.

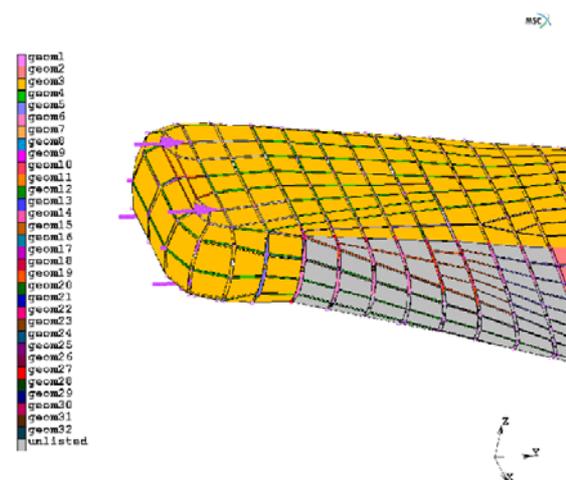
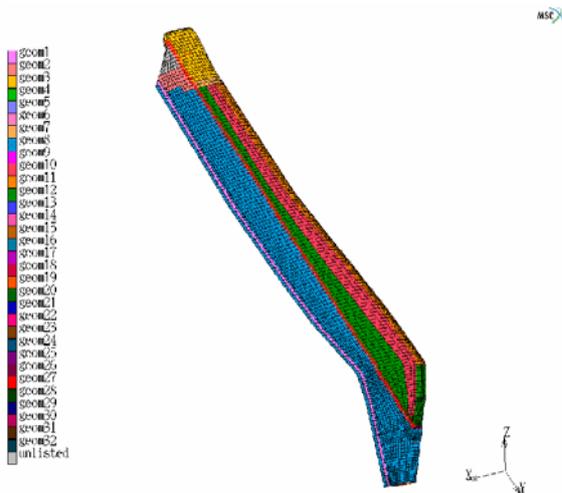


Fig.3.- Meshing of the blade root

The result obtained for the complete blade is a 3D FE model of less than 10000 nodes and of about 13000 elements: cf. Fig. 4. Such FE model leads to reasonable time computation, about 30 minutes for a modal computation of the rotating

blade on a middle range powered Hewlett-Packard



workstation.

Fig.4.- The 3D FE model of the ERATO blade

### Validation of the 3D FE model

The 3D FE model has already been elaborated with some blade sections validated (cf. previous section). The validation of the whole blade will be made, based on measurements of the weight and the position of the center of mass of the blade, of the modes of the blade clamped at its root end and those of the blade suspended at a ceiling. The calculations are based on the MSC/Marc code, using two different FE models, the 3D FE model and the (1D+2D) FE model elaborated with the sectional mechanical properties provided by DMSE. The calculations of modal frequencies for the clamped blade are also made by DMSE, based on a code developed in-house. There are some difficulties for making the correlation study between experiments and calculations, i.e. one needs to reproduce the experimental conditions. The particular question of clamping the blade is not well reproduced in calculations, for the reason that a very tight clamping is not realizable experimentally. The free-free configuration is preferred, but unfortunately it was not considered in experiments on the ERATO blade.

### Weight and position of the center of mass of the blade

Measurements of the weight and of the position of the center of mass have been made for the blade without and with its measurement sensors. The blade is heavily instrumented, strain and pressure sensors with the electric wiring represent about 7 % of the total weight. From the practical viewpoint of modeling, only the wires put along the torsion box are modeled by beam

elements. The experimental values are reported in Table 2, with the calculated values by the MSC/Marc code.

Table 2.- Mass and position of the center of mass of the blade (blade series 1: DMSE ONERA, blade series 2,3: DLR)

Model without sensors	Mass	Position of the center of mass
Experiments Blade series 1	2930 g	$X_G = -3.9 \text{ mm}$ , $Y_G = 987.3 \text{ mm}$
3D FE model	2907 g	$X_G = -3.1 \text{ mm}$ , $Y_G = 987.0 \text{ mm}$

Model with sensors	Mass	Position of the center of mass
Experiments Blade series 1	3255 g	$X_G = 0.4 \text{ mm}$ , $Y_G = 987 \text{ mm}$
Blade series 2	3143 g	$X_G = 1.4 \text{ mm}$ , $Y_G = 1002 \text{ mm}$
Blade series 3	3194 g	$X_G = 2.7 \text{ mm}$ , $Y_G = 972 \text{ mm}$
3D FE model	3143 g	$X_G = -0.16 \text{ mm}$ , $Y_G = 995 \text{ mm}$

There are uncertainties in experimental fabrication, as reflected in the variation of the position of the center of mass according to the fabrication series for the instrumented blade; however, they cannot be quantified. The correlation between experimental and calculated results is good for the blade without sensors, it deteriorates but remains satisfactory for the instrumented blade.

### Modes of the blade clamped at its root

Modal frequencies of the blade clamped at its root through two bolts have been made. Relative errors between experimental and calculated values of modal frequencies are reported in Table 3. Calculations are made with two different beam models and with the 3D FE model. The two beam models are elaborated with the same 2D mechanical properties, but according to two different codes, the DMSE code and the MSC/Marc code respectively. They provide different values for modal frequencies, the largest discrepancy occurs for the fourth mode (overestimating for the former code and underestimating for the second). It appears that the best correlation is obtained with the 3D FE model, less than 3% relative error.

Table 3.- Relative errors on calculated modal frequencies of the ERATO blade clamped at its root

Modes	Beam 1 DMSE	Beam 2 MSC/Marc	3D FE MSC/Marc
Flap	- 5 %	- 8 %	+5 %
Lead-Lag	+ 6 %	+3.5 %	+3 %
Flap	- 5 %	- 7 %	+ 1 %

Flap	+12 %	- 4 %	- 1 %
Torsion	+1 %	- 1.5 %	+1 %
Flap	- 3 %	- 3.5 %	- 1 %

Corresponding to each modal frequency, nodal lines (lines with no displacements) have been also recorded in experiments. Minimum deflections are also obtained for the clamped blade at various modal frequencies and are reported in Fig.5. One can note a good correlation between calculated and experimental results, the worst occurs for the third mode.

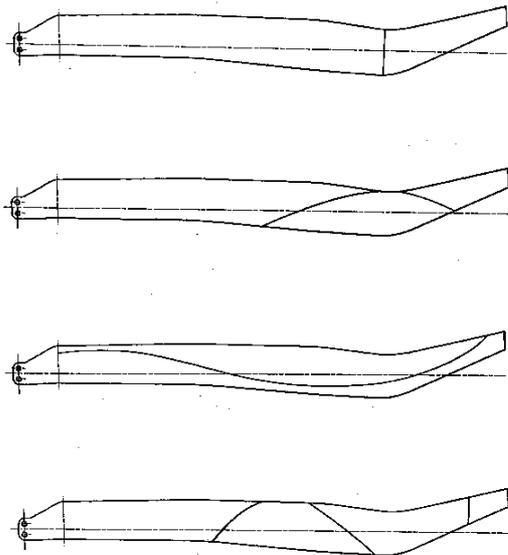


Fig. 5a/ Experimental nodal lines associated with the modes 3,4,5 and 6 of the clamped blade

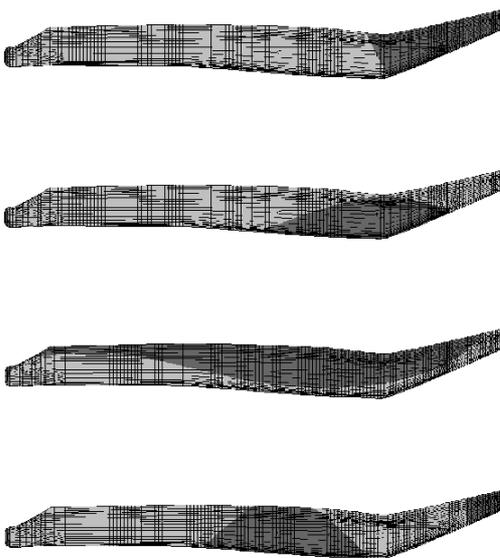


Fig. 5b/ Predicted nodal lines associated with the modes 3,4,5 and 6 of the clamped blade

### Modal frequencies of the suspended blade

The mechanical system is constituted of an iron mass coupled through a thin plate made of special iron to another iron mass, on which the blade is attached by two bolts. The thin plate only allows flapping motion. To get accurate results by numerical simulation, the mechanical system has been modeled by finite elements. Relative errors between experimental and calculated results are reported in Table 4: the best agreement is obtained with 3D FE model. The highest relative error for the 3D FE model occurs for the first mode, of about 5 % but it is less than 0.75 Hz in absolute magnitude. One can remark that the lead-lag frequency predicted by the two FE models is overestimated. The 3D FE model overestimates the torsion frequency in both experimental configurations.

Table 4.- Relative errors on calculated modal frequencies of the ERATO blade hung to a ceiling

Modes	Beam model 2 MSC/Marc	3D FE model MSC/Marc
Flap	- 9 %	+ 5 %
Lead-Lag	+ 8 %	+ 3 %
Flap	- 9 %	- 1 %
Flap	- 6 %	+ 1 %
Torsion	- 0.5 %	+ 2 %
Flap	- 7 %	- 1.5 %

To summarize, the 3D FE model is validated satisfactorily. It is possible to obtain a better correlation between predicted and experimental results by playing on the values of various materials parameters of the blade that are only known within certain uncertainties.

### Predictions of the 3D FE model for torsion deflection

The main motivation of this study is the explanation of discrepancies observed between experimental results and predictions of the aeroelastic behavior of the blade [Ref 10]. The predictions were based on the aeroelastic code R85 of Eurocopter. This code is not presently in use and it is replaced by the comprehensive helicopter aeroelastic code HOST. The calculations with the latter don't provide any better results. One of the most intriguing feature observed for the ERATO

blade is the high content in torsion deflection in advancing flights. We will consider in the next subsection the modes of the rotating ERATO blade.

### Campbell diagram

Modal frequencies of the rotating blade are obtained in structural codes in two steps: establishment of a periodic equilibrium regime in order to get the correct geometric stiffness, then modal analysis. The latter analysis with the MSC/Marc code doesn't take into account the Coriolis terms because the solver doesn't encompass antisymmetric matrix. The Coriolis effects may become important, as pointed by Laurenson [Ref 4] on a rotating beam having important coning angle. For the ERATO blade that has non negligible sweep angles on the outboard 20 % R (R: blade radius) of the blade of about 20 degrees, it cannot be assumed that Coriolis effects are negligible.

To determine the Coriolis effects, the following procedure is considered: the blade is submitted to nodal excitation with appropriate direction and its time response is analyzed for its Fourier spectrum. The importance of the Coriolis effects will be reflected in the difference of values of frequencies given by the Fourier spectrum of the time response and those of the modal analysis. For the beam model, it is found that Coriolis effects are negligible. For the 3D FE model, these effects are also not important.

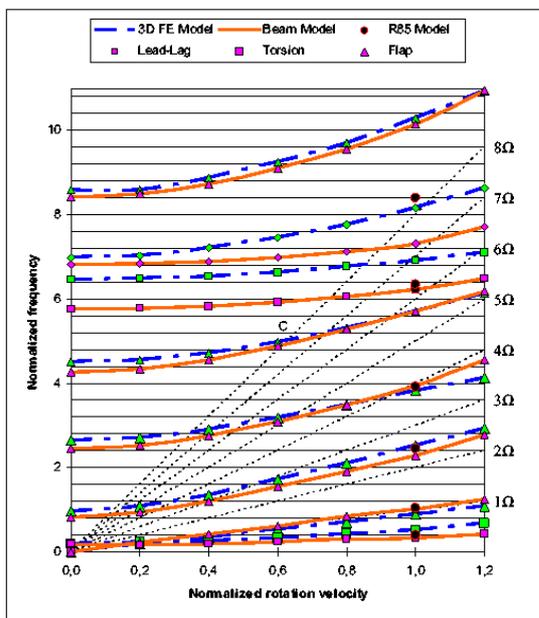


Fig. 6.- Campbell diagram for the ERATO blade

The Campbell diagram (modal frequencies versus rotation speed) is shown in Fig. 6: for confidentiality reasons, the frequencies are

normalized to a constant value. In Fig. 6, are also reported the values obtained by the R85 code. The first two frequencies obtained for the beam model by modal analysis are not reliable, so they are calculated by Fourier analysis of the time response of the beam model.

For the first five modes, the beam model and the 3D FE model nearly give the same results. Differences occur for the sixth mode that is the second lead-lag mode and the seventh mode, the first torsion mode. The variation of the torsion mode with rotation speed predicted by the 3D FE model is larger than the one by the beam model. The R85 code predicts the first four modes in agreement with the 3D FE model, but overestimates the values of the fourth elastic flap frequency and the first torsion frequency whereas the value of the second lead-lag frequency is underestimated.

### Modal shape of the third elastic flap mode

For the ERATO blade that has a complex geometric shape, flap modes are not pure and can involve torsion deflections. It is interesting to

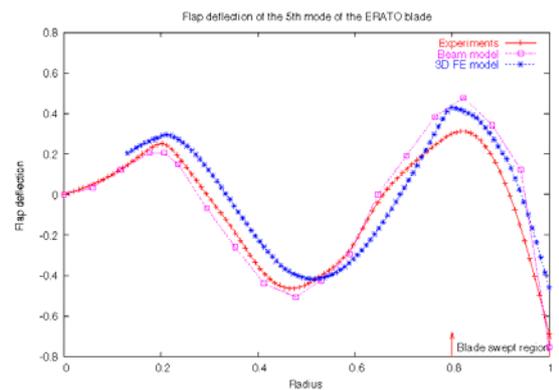


Fig.7a/ Measured and predicted flap deflections of the third elastic flap mode of the rotating ERATO blade

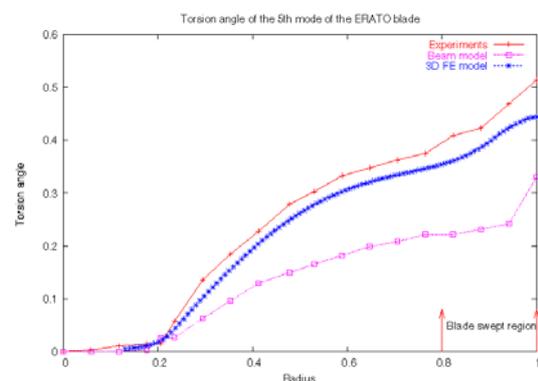


Fig.7b/ Measured and predicted torsion deflections of the third elastic flap mode of the rotating ERATO blade

analyze the modal shape of the third elastic flap mode. In [Ref 10], the modal shape of this mode

has been extracted within certain theoretical assumptions of the Strain Pattern Analysis from experiments: flap and torsion deflections are reported in Fig. 7 versus the span distance from the rotor center. The same quantities calculated with the R85 code, based on the beam model, and with the MSC/Marc code, based on the 3D FE model are also reported in Fig. 7. These quantities are normalized to the difference of amplitude between the maximum of the blade deflection near the blade root and its minimum near the middle of the blade. Such normalization is based on the fact that the beam model and the 3D FE model should provide the same predictions for the rectilinear part of the blade. For flap deflections reported in Fig. 7a/, the two FE models are in agreement with the experiments, within experimental errors.

For torsion deflections shown in Fig. 7b/, the predictions show less good agreement with experiments and the best correlation with experimental results is obtained with the 3D FE model. The comparison between the two FE models is interesting:

(i) the torsion deflection predicted by the beam model is smaller than the one by the 3D FE model, even in the rectilinear region of the blade;

(ii) in the blade swept region, the beam model predicts a rapid variation of the torsion deflection.

The high content of torsion deflection in the third elastic flap mode seems to influence the variation of its modal frequency with rotation speed: the variation predicted by the 3D FE model is less rapid than the one by the (1D+2D) model. For other modes, such as the first and fourth elastic flap mode, the two FE models predict the same variation with rotation speed. Based on the observation of such variation, the second elastic flap mode should also contain a higher content of torsion deflection than predicted by the beam model.

To summarize, the 3D FE model favors high content of torsion deflection in the third elastic flapping mode (and probably for the second elastic flap mode). This feature could explain the high harmonic 5/rev of the torsion at the blade tip in advancing flights. In Fig.8, are reported the harmonics multiple of 1/rev of the torsion of a typical flight with lift coefficient equal to  $Z = 12.5$ . Components 4/rev and specially 5/rev are important, such feature is not predicted by the R85 code.

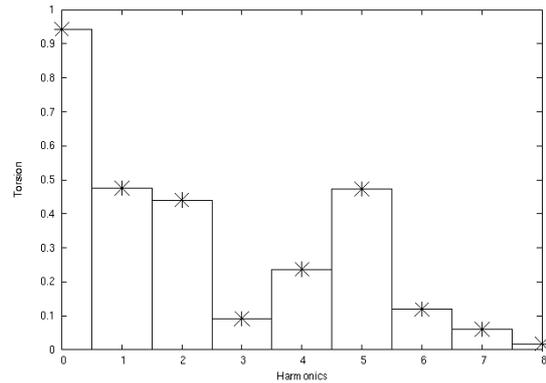


Fig.8.- Harmonic decomposition of the torsion at the blade tip for a typical advancing flight

### Conclusion

An important effort has been carried on developing an engineering approach for the elaboration of a 3D FE model of a helicopter rotor blade, sufficiently realistic with a number of nodes restricted to the minimum, therefore with no heavy computational demands. The blade is divided into various segments bounded by sections that are defined by the manufacturer in terms of material and geometric lay-outs. Meshing is done for each segment consecutively, starting from inboard and outboard surfaces. The procedure has been applied to the ERATO blade that has a planform shape deviating largely from the classical rectangular one, the 3D FE model involves less than 10000 nodes.

The numerical tools used are the MSC/Patran code for meshing and the MSC/Marc code for calculations. The latter has been chosen for its capabilities in treating nonlinear dynamics. It has been tested with success against various cases representative of the helicopter rotor blade, except the one with curved composites.

The 3D FE model of the ERATO blade has been validated against measurements of modes of the blade clamped at its root and those of the blade suspended to a ceiling. The predictions of the 3D FE model correlate with experimental results better than those of the (1D+2D) model, within 5 % relative error. Given the many uncertainties on the blade materials properties, the blade fabrication, the experimental conditions (clamping for instance) and on the accuracy of predictions of the MSC/Marc code, this result is satisfactory.

It has been found, in the course of this study, that previous calculations made at ONERA for the aeroelastic behavior of the ERATO blade were not accurate enough due to incorrect predictions of dynamics of the rotating blade.

One distinct feature of the 3D FE analysis from the (1D+2D) FE analysis is about the high content of torsion deflection in the third elastic flap mode (and probably the second elastic flap mode).

Such characteristic could explain the high content in 5/rev for the torsion at the blade tip observed at typical advancing flights.

Further studies are being carried for coupling dynamics with simple aerodynamics (nodal forces, aerodynamic coefficients), before going to the consideration of CFD aerodynamics. This research will lead to predictive capabilities on the performance of the “ultimate rotor blade” involving large freedoms in varying geometric and material lay-outs.

### Acknowledgements

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### References

Ref 1 : J. Prieur, W.R. Spletstoesser  
*Erato: an ONERA-DLR cooperative program on aeroacoustic rotor optimisation*  
25<sup>th</sup> European Rotorcraft Forum, Roma (Italy), September 14-16, 1999

Ref 2 : L. Buchaniek, P. Geoffroy, H. Mercier des Rochettes  
*Développement technique probatoire ERATO - Définition finale du rotor: Réalisation et caractérisation des pales technologique et prototype*  
Rapport ONERA Lille no 97/39 Octobre 1997

Ref 3: P. Geoffroy, H. Mercier des Rochettes  
*Développement technique probatoire ERATO - Définition finale du rotor: Etude de conception structurale de la pale optimisée aéroacoustiquement*  
Rapport ONERA Lille no 97/30 Mai 1997

Ref 4 : R.M. Laurenson,  
*Modal Analysis of Rotating Flexible Structures*  
AIAA Journal, Vol.14, No.10, pp.1144-1450.

Ref 5 : J.Minguet, J.Dugundji  
*Dynamics and analysis for composite blades under*  
AIAA Journal, Vol.28,No.9, 1990, pp.1573-1579

Ref 6 : J.Minguet, J.Dugundji  
*Experiments and analysis for composite blades under large deflections, Part II.- Dynamic behavior*  
AIAA Journal, Vol.28,No.9, 1990, pp.1580-1588.

Ref 7 : E.H. Dowell, J. Traybar, D.H. Hodges  
*An experimental-Theoretical Study of Nonlinear Bending and Torsion Deformation of a Cantilever Beam*  
J. Sound Vib., vol. 50 no 4, 1977, pp. 533-544

Ref 8 : private communication  
H. Mercier des Rochettes

Ref 9 : D. Joly  
*Validation des calculs de rigidité de torsion par éléments finis de pales d'hélicoptère*  
Rapport Technique ONERA RT 1/05740 DMSE, Mars 2002

Ref 10: P. Leconte  
*ERATO Phase 3. Dynamic analysis of the tests of the 7AD and ERATO rotors in SIMA and DNW wind tunnels*  
Technical Report ONERA RT 24/4374 DDSS/Y, July 1999