EIGHTEENTH EUROPEAN ROTORCRAFT FORUM

E - 10

Paper No 6

# The Measurement of Blade Deflections

## a new implementation of the strain pattern analysis

Nicolas Tourjansky and Edmond Széchényi

ONERA, Châtillon, France

September 15-18 1992

Avignon, France

ASSOCIATION AERONAUTIQUE ET ASTRONAUTIQUE DE FRANCE

# The Measurement of Blade Deflections

## a new implementation of the strain pattern analysis

Nicolas Tourjansky and Edmond Széchényi

ONERA, Châtillon, France

## 1. Introduction

The measuring of helicopter blade deflections in flight has been an objective of manufacturers and researchers for a long time. Different methods using either optical or strain measurements have been tried.

The method based on a strain patterns analysis (SPA) is well known (see for example ([1] and [2]) and is the only one that has been put into practice. Though this method is theoretically exact, attempts at using it have either been very limited in scope or have resulted in unacceptably large experimental errors.

The principle behind this method is the identification of calibration strain patterns in the strain pattern measured during operation. The calibration patterns are each obtained for known deflections of the blade. The obvious choice for the calibration deflection set is the normal mode shapes.

A thorough study of the identification procedure and of the required experimental accuracy reveals that the essential difficulty encountered in past applications of this method resides in the similarity of some of the modal strain patterns (e.g. 1st torsional and 1st bending modes).

The use of gauge bridges that exclusively measure either bending or torsion goes some way to alleviating this problem. Even then, potential difficulties with similar strain patterns are not entirely avoided as these can well exist when modes are not pure in coordinate directions. Moreover, the separation of component deflections can be realistic only on the basis of the non-rotating characteristics of a blade. Rotation modifies apparent blade stiffness, blade normal modes and mode shapes and hence gauge bridges will not correctly separate the different deflection components on rotating blades.

In this paper a method is proposed which overcomes the encountered difficulty by instrumenting the blades with strain gauges in such a manner as to give modal strain patterns that clearly characterise each mode. There is almost total freedom in the way the strain gauges can be placed on blades.

Laboratory tests on a beam have shown the robustness and reliability that this strain gauge implementation gives the strain pattern analysis.

Extensive blade deflection measurements have been conducted on rotors in wind tunnels yielding a vast data base to be used for code validation. First computations have shown surprisingly close predictions of both torsional and flap deflections.

# 2. The Strain Pattern Analysis method

Deflection and twist angles can theoretically be calculated by a double integration of strains. However, apart from requiring local blade characteristics, this needs a large number of measuring stations and even then the results obtained are totally unreliable because the merest experimental errors in strain can cause large errors in the integrated result. The method described here is known (see [1] and [2]). It is quite different and much simpler.

Strictly speaking, any arbitrary deflection of a structure can be considered as a weighted sum of an *infinite* number of different basic shapes. For convenience, the shapes considered will be exclusively those of the normal modes. A mode shape is defined as the deflection of a structure when it vibrates freely at one of its eigenfrequencies.

In practice, only a relatively small number of modes shapes needs to be considered. For example, the bending deflection of a cantilevered beam with a point load at the free end can be determined with good accuracy as a weighted sum of only its first two normal mode shapes. The same can be said of torsional modes when a torque is applied at the free end.

Of course, this supposes that the end conditions of the structure are invariant: the more they vary, the more modes will be required. Though the end conditions of helicopter blades can be considered as constant, centrifugal forces modify mode shapes somewhat so that these will change a little with turning speed. It may therefore be necessary to consider a larger number of modes if non-rotating modes are considered for the deflections of a rotating blade.

The same principle of modal superposition holds for strains. Therefore a measured strain pattern on an operating helicopter blade is merely the sum of weighted modal strain patterns. If the latter are known, an identification procedure will give the influence of each modal strain pattern in the total strain pattern. These modal influence coefficients are then the modal weighting functions necessary to calculate deflections through mode summation.

The method is shown in the following simple equations. The principle of modal superposition can be expressed by:

$$w(r,t) = \sum_{i=1}^{s} \phi_i(r)\ q_i(t) \tag{1}$$

where

$w(r,t)$ is the deflection of the point $r$ at time $t$
$\phi_i(r)$ is the deflection of mode $i$ at point $r$
$q_i(t)$ is the unknown generalised coordinate (influence coefficient or weighting function)
$s$ is the number of modes considered

Similarly, it is assumed that strains on a blade can be expressed by:

$$M(r',t) = \sum_{i=1}^{s} \phi_i(r')\ q_i(t) \tag{2}$$

where

$M(r',t)$ is the deflection of the point $r'$ at time $t$
$\phi_i(r')$ is the deflection of mode $i$ at point $r'$

In matrix form, let –

$$\{\phi\} = \begin{matrix} \phi_1 \\ \phi_2 \\ \cdots \\ \cdots \\ \phi_s \end{matrix} \qquad \{\sigma\} = \begin{matrix} \sigma_1 \\ \sigma_2 \\ \cdots \\ \cdots \\ \sigma_s \end{matrix} \qquad \{m\} = \begin{matrix} q_1 \\ q_2 \\ \cdots \\ \cdots \\ q_s \end{matrix}$$

Equations 1 and 2 then become –

$$w(r,t) = \{\phi(r)\}^T \ \{q(t)\} \tag{3}$$

$$M(r',t) = \{\sigma(r')\}^T \ \{q(t)\} \tag{4}$$

The blade mode shapes $\{\phi\}$ are determined experimentally using any of the well known techniques available. The modal strain patterns $\{\sigma\}$ are measured simultaneously at $m$ measuring stations on the blade, where $m \geq s$.

When the blades are under load, the strain pattern is measured at time $t$ at the $m$ measuring stations:

$$M(r'_1,t),\ M(r'_2,t),\ \ldots\ldots,\ M(r'_m,t)$$

The deviation (error) between the measured strains at the point $r'$ and the values estimated in equation 4 is:

$$\epsilon(r',t) = \{\sigma(r')\}^T \ \{q(t)\} \ - \ M(r',t)$$

An overall total error can be expressed by the sum of the squares of the deviations at the m points. Conditions for a minimum error are obtained by equating the partial derivative of this total error to zero.

Now let $\{M\}$ be the strain pattern measured under load:

$$\{M\} = \begin{matrix} M_1 \\ M_2 \\ \cdots \\ \cdots \\ M_m \end{matrix}$$

and $[S]$ be the $s,m$ matrix: $[\{\sigma\}_1, \{\sigma\}_2, \ldots\ldots, \{\sigma\}_m]$. It is then easy to show that –

$$\{q(t)\} = ([S]\ [S]^T)^{-1}\ [S]\ \{M\} \tag{5}$$

Once the influence coefficients, $q(t)$, are obtained through this least square method, the deflections, $w(r,t)$, are calculated using equation 3.

# 3. Application of the method

Though the measuring technique described above is theoretically sound, it is very sensitive to experimental details. The principles described are well known but the applications have generally been very poor. The reasons for these difficulties were thoroughly investigated. It was found that the quality of the deflection measurements rests on a number of factors but mainly on the following two conditions:

— A sufficient number of modes for equations 1 and 2 to be valid. To satisfy this condition it is best to take the largest number that can be correctly and conveniently measured. To reduce the need for a large number of modes to a minimum, it is necessary to ensure that the shapes are measured with similar end conditions as when the blades are operating.

— A good modal strain identification. This condition is delicate as it depends on a number of factors such as the accuracy of the strain measurements, the number of strain measuring stations and above all the pattern of the modal strains.

The last mentioned criterion is by far the most important. This is perhaps best illustrated by considering a cantilevered beam instrumented with a large number of evenly spaced strain gauges, all placed in an identical fashion so as to detect both out of plane deflections and twist (figure 1). The modal strain patterns obtained for the out-of-plane and torsional modes of this beam are almost identical (figure 2). This is also true for other mode orders.

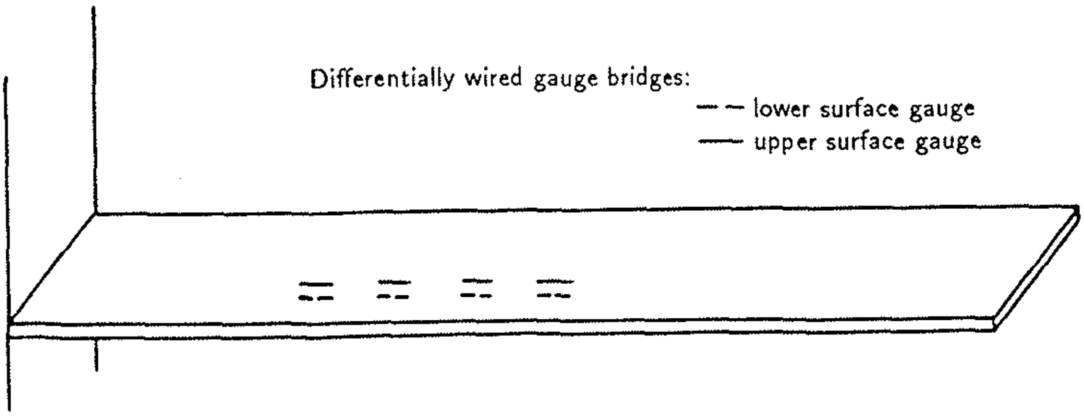



*Figure 1 : Beam with regular strain gauge instrumentation*

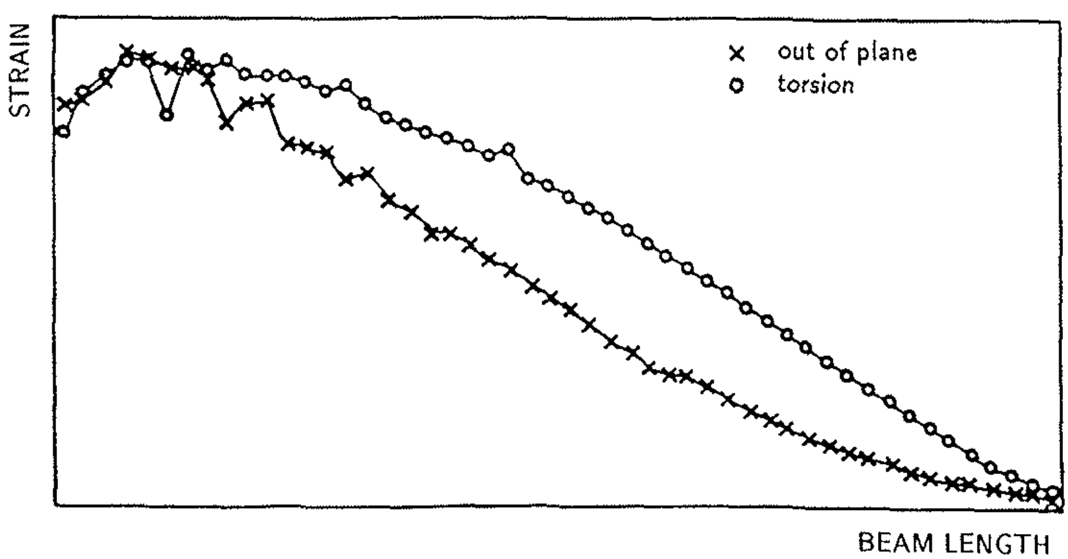



*Figure 2 : Modal strain patterns for the fundamental modes*

Any modal identification using such similar modal strain patterns will lead to very large errors, even if the experimental errors are extremely small. For example, if the strain pattern to be identified is due exclusively to a torsional moment, the identification will invariably detect components in bending.

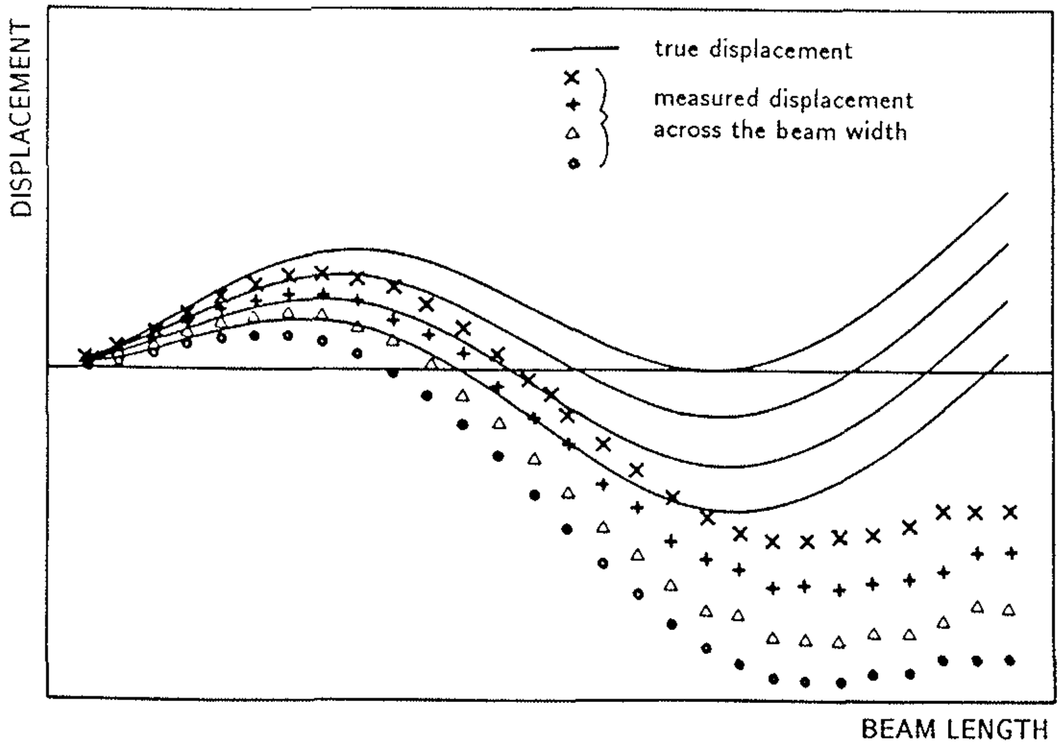



*Figure 3 : Twist-bending displacements with regular gauge instrumentation*

Figure 3 shows a case where the beam in figure 1 is experiencing combined bending and twist. This is obtained by changing the dynamic characteristics of the beam with added masses and measuring the displacements when exciting one of the new modes. The results of the identification clearly give large components of the 1st bending mode. This is obviously wrong when compared to the direct deflection measurements.

A solution that is usually adopted in an attempt to overcome this problem is to instrument the structure with strain gauge bridges measuring exclusively either torsion or one of the two orthogonal bending components and then making three separate modal identifications. This technique seems to be a reasonably easy solution for a homogeneous straight beam for which the strain distributions are well known and whose modes are naturally separated into the three previously mentioned types (torsion and two orthogonal bending).

Reality for helicopter blades or any more complex shaped beams is different. The structure, the chord variation and the twist make strict separation into component modal strain patterns hazardous and pure bending or torsion modes are the exception rather than the rule. Therefore, **a viable solution can only be obtained by placing the strain gauge bridges in such a way that no two modes will have the same or similar modal strain patterns**, whatever these modes are.

An example of this is shown in figure 4 for the beam considered in figure 1. The resulting modal strain patterns of the fundamental bending and torsional modes are shown in figure 5 (compare with figure 2). Deflections obtained with the same combined twist and bending deflections as in figure 3 are shown in figure 6. The improvement in the result is striking.

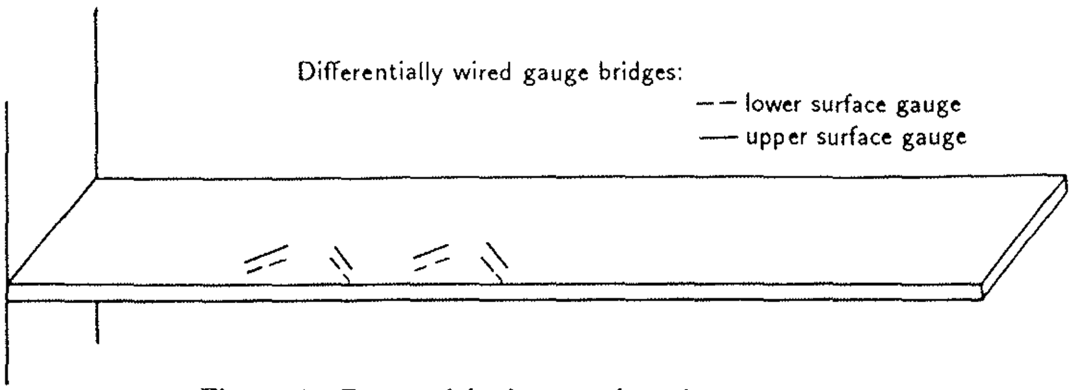



*Figure 4 : Beam with alternated strain gauge instrumentation*

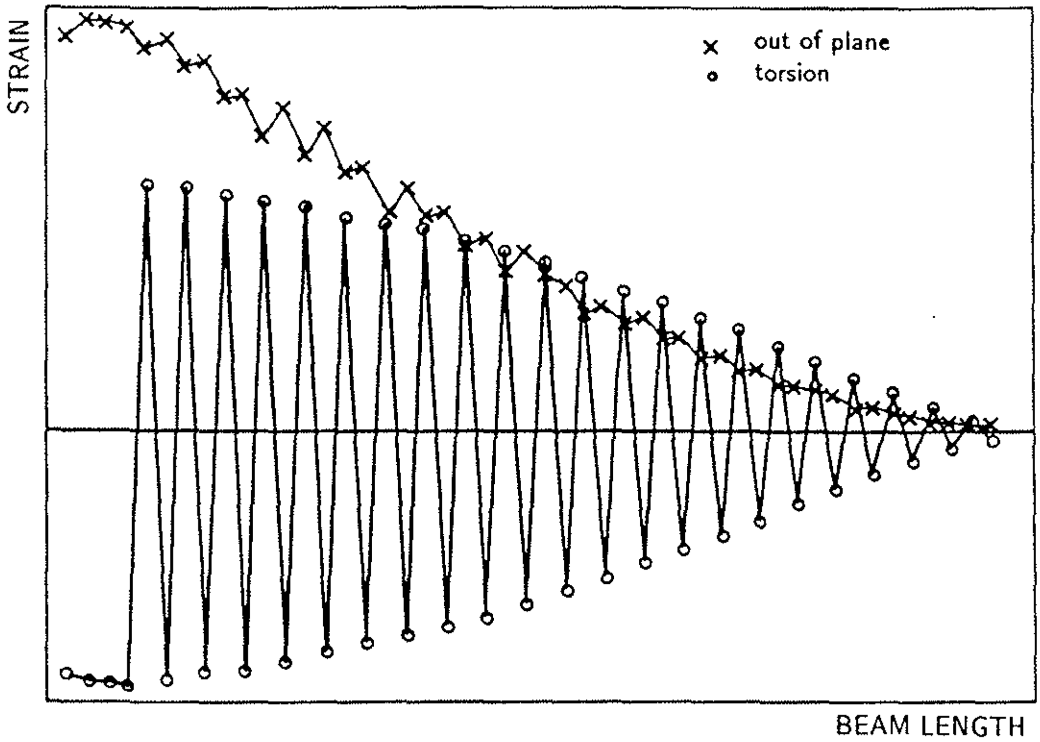



*Figure 5 : Modal strain patterns with alternated gauges*

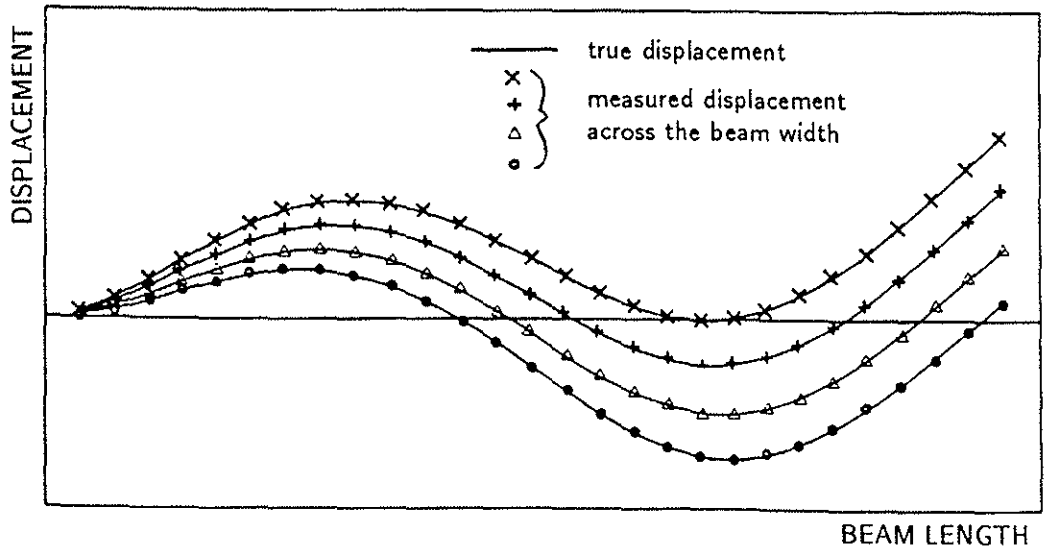
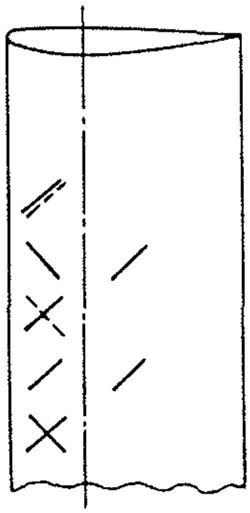



*Figure 6 : Displacements using alternated gauges for the same conditions as in Figure 3.*

The gauge positioning procedure is not as difficult as may at first appear. An optimum solution is not required and fairly simple rules of thumb can be applied. these consist essentially in:

— ensuring that centrifugal forces and cyclic gravity forces are eliminated through fully compensated gauge bridges;
— placing bending stress measuring gauge bridges alternating spanwise for the two orthogonal planes;
— varying the gauge measuring axes so that torsional and bending strains have very different spanwise patterns.

Figure 7 shows schematically gauge configurations that can be alternated along the blade span to give good pattern separation. Alternating configurations **a** and **b** (see figure) is best as these give an optimal amount of information with large strain pattern differences.



| | in plane | out of plane | torsion |
|---|---|---|---|
| a | 0 | 1 | 1 |
| b | 1 | 0 | −1 |
| c | 0 | 1 | 0 |
| d | 1 | 0 | 0 |
| e | 0 | 0 | 1 |

*Figure 7 : Possible gauge configurations that can be alternated*

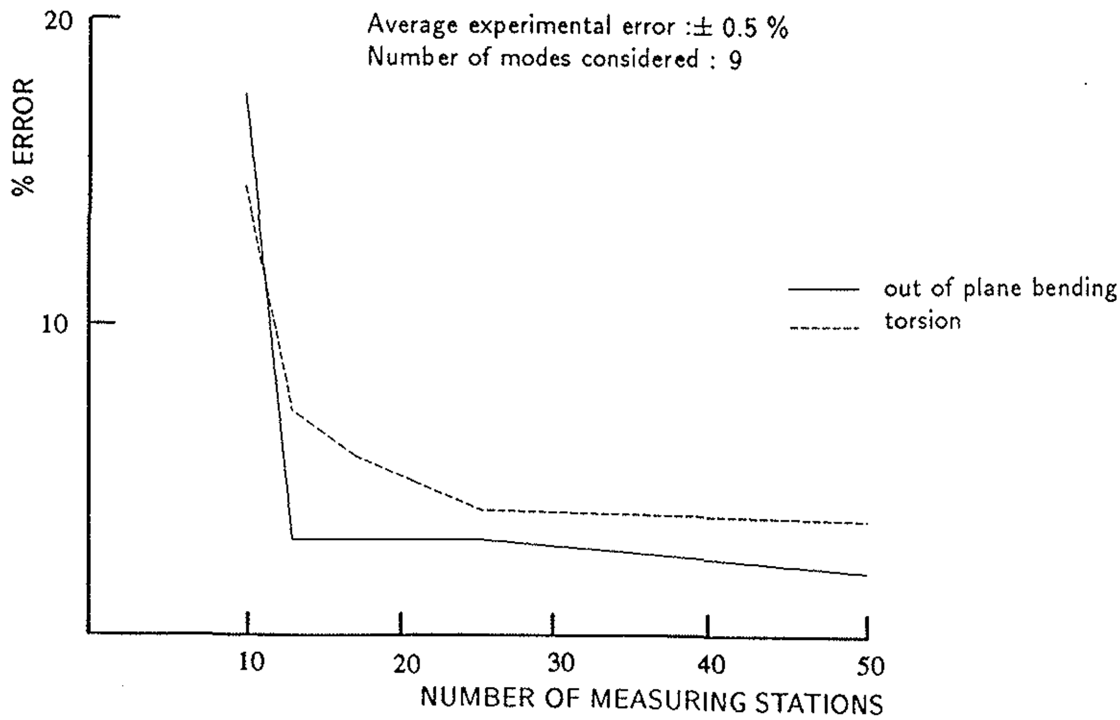



*Figure 8 : Displacement errors as a function of the number of gauges*

The number of strain gauge bridges required depends on the expected quality of the measurements. With no experimental error, the number of stations must be at least equal to the number of modes considered. In practice one and a half times the number of stations as modes considered is more than sufficient to give good results. Figure 8 shows the deflection measuring errors as a function of the number of gauges for a simulated case where the strains are measured with errors not exceeding 5%.

Gauges that do not operate correctly must of course be completely eliminated from the data base as the large errors they will convey can totally destroy the final result. It has been shown that a good quality result is never sensitive to the presence or absence of any one correctly functioning gauge. This is the basis for a method for checking the quality of any one gauge measurement: each gauge is eliminated in turn and each time the deflections are calculated. If the results vary by more than about 5% relative to the average value, then the gauge is definitely eliminated and the average value is once again computed.

# 4. Measurements on rotors

## 4.1. Description of the rotors

The above measuring technique was used during helicopter rotor model wind tunnel tests. Two different rotors were instrumented:

(i) 1.5$m$ diameter 3-bladed rotor with soft-in-torsion blades fitted with a variable angle tab. Apart from measuring torsional amplitudes, an objective was to validate the deflection measurements in both bending and torsion since the facility allowed simultaneous optical blade tip trajectory measurements over a small portion of the rotation.

(ii) 4.2$m$ diameter 4-bladed rotor. The deflection measurements on this rotor show typical helicopter behaviour. Two blade tips were tested: rectangular and swept.

For both rotors 25 strain gauge bridges were installed according to the pattern of figure 4 (configuration a of figure 7 alternated directionally). Only flap and twist deflections were measured.

Both the mode shapes and the corresponding modal strain patterns were measured in the laboratory on the instrumented blades prior to the wind tunnel tests. Though the measured modes were non-rotating, care was taken to create blade root end conditions as close as possible to those of the actual rotors. In both cases the blades were hinged.

## 4.2. Deflection measurements

Some of the torsional deflections obtained on the smaller rotor were compared to optical measurements. A typical result is shown in figure 9 for torsion for a case with a blade tab angle of 12$^0$. The scatter of the optical measurement is partially due to the fact that the values are instantaneous and deflections vary from cycle to cycle, just as the loads do. Other sources of error are inherent to the optical method which relies on the control position values in order to determine the exact blade position in space.

The strain pattern analysis measurements are all averaged over 30 consecutive cycles. They can of course be obtained for a single rotation.

The strain pattern analysis measurements are perfectly repeatable as shown in figure 10 where deflections are measured at three different times on the smaller rotor for almost identical flight conditions ($C_T/\sigma = 0.075$, advance ratio $\mu = 0.4$, tab angle $= 0^0$).

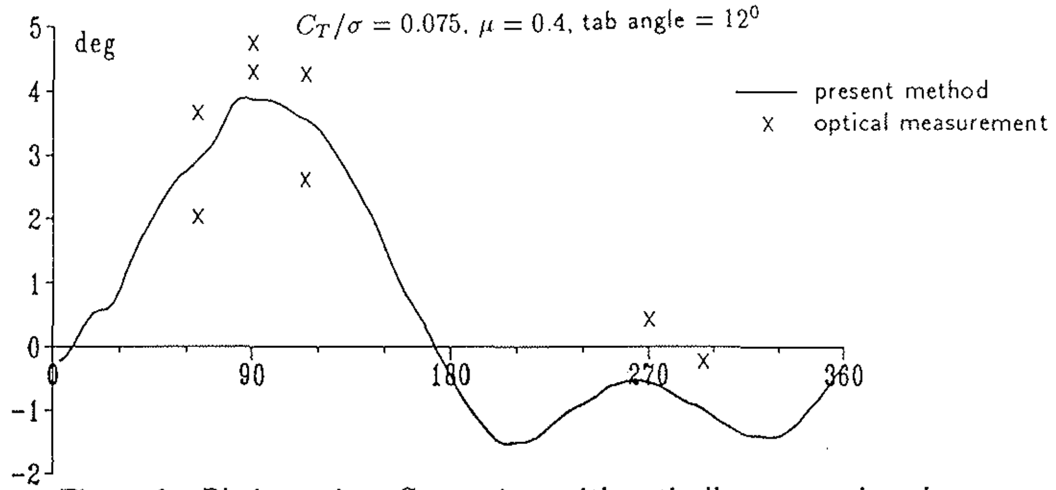



*Figure 9 : Blade torsion. Comparison with optically measured angles*

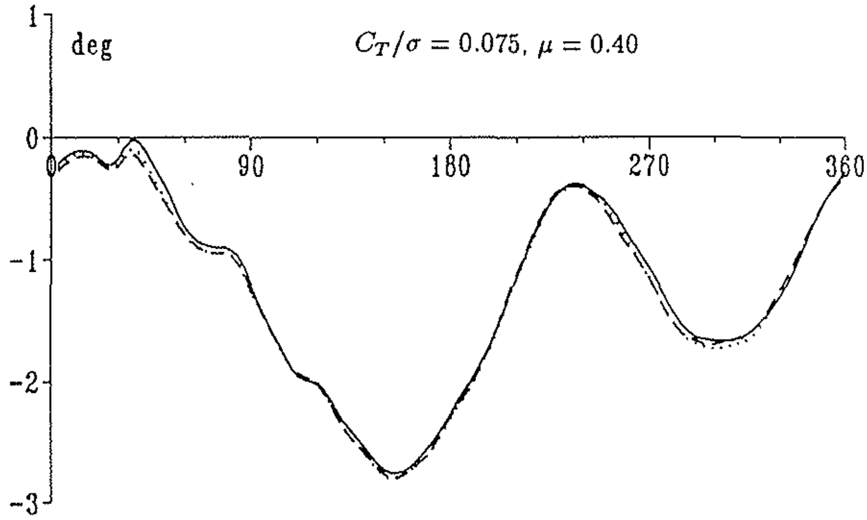



*Figure 10 : Repeatability of blade deflection measurements*

## 4.3. Blade deflection as a function of flight conditions

Though bending amplitudes may be of some academic interest, it is the torsional twist that affects the rotor performance and behaviour. Thus, in the few examples shown below only torsional deflections are discussed.

Figures 11 and 12 (larger rotor) show twist at the blade tip as a function of azimuth with varying advance ratio ($\mu$) and blade loading ($C_T/\sigma$) respectively. As expected, the effect of forward speed on the blade twist appears only in the retreating blade part of the rotation and specifically at high speeds when there is flow separation and perhaps local stall. The effect of increasing load progressively increases the twist angle. The surprisingly large twist angles for this stiff-in-torsion blade should be noted.

Figure 13 (larger rotor) is a typical example of the effect of the blade tip shape. The swept tip has a larger moment than the rectangular tip and therefore twists more.

Figure 14 (smaller rotor) illustrates the effect of the tab angle. The blade behaviour changes entirely due to the large positive moments induced by positive tab angles.

Figure 15 gives typical spanwise twist angles and bending blade displacements at different azimuthal positions of the blade for the smaller rotor. The inflection of the torsion near the tip is caused by a discontinuity in the structure due to the blade tip fixture.

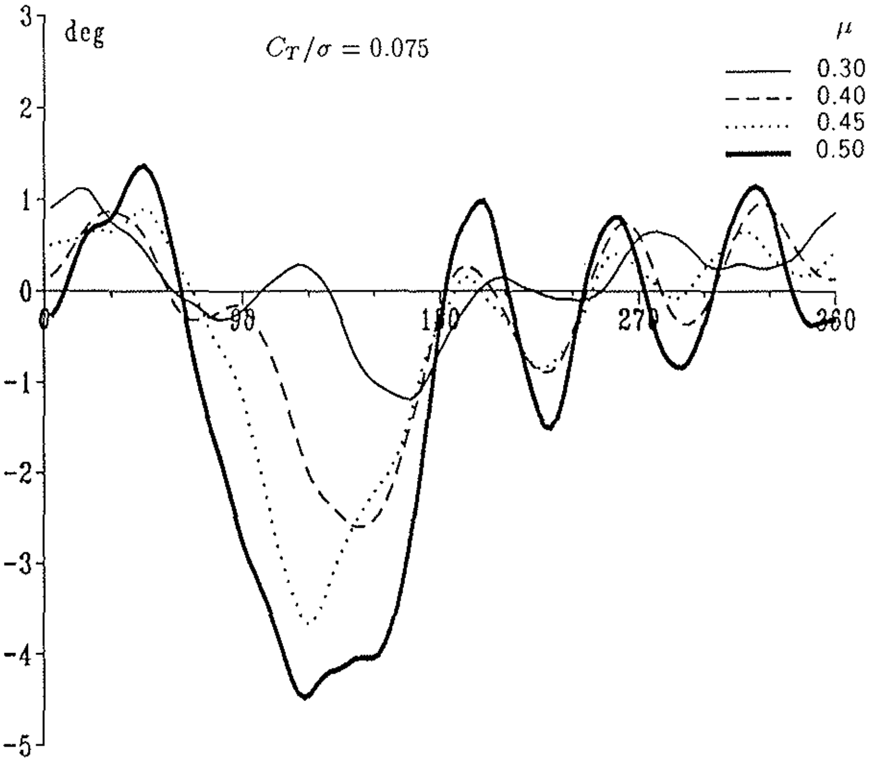



*Figure 11 : Twist with varying forward speed*

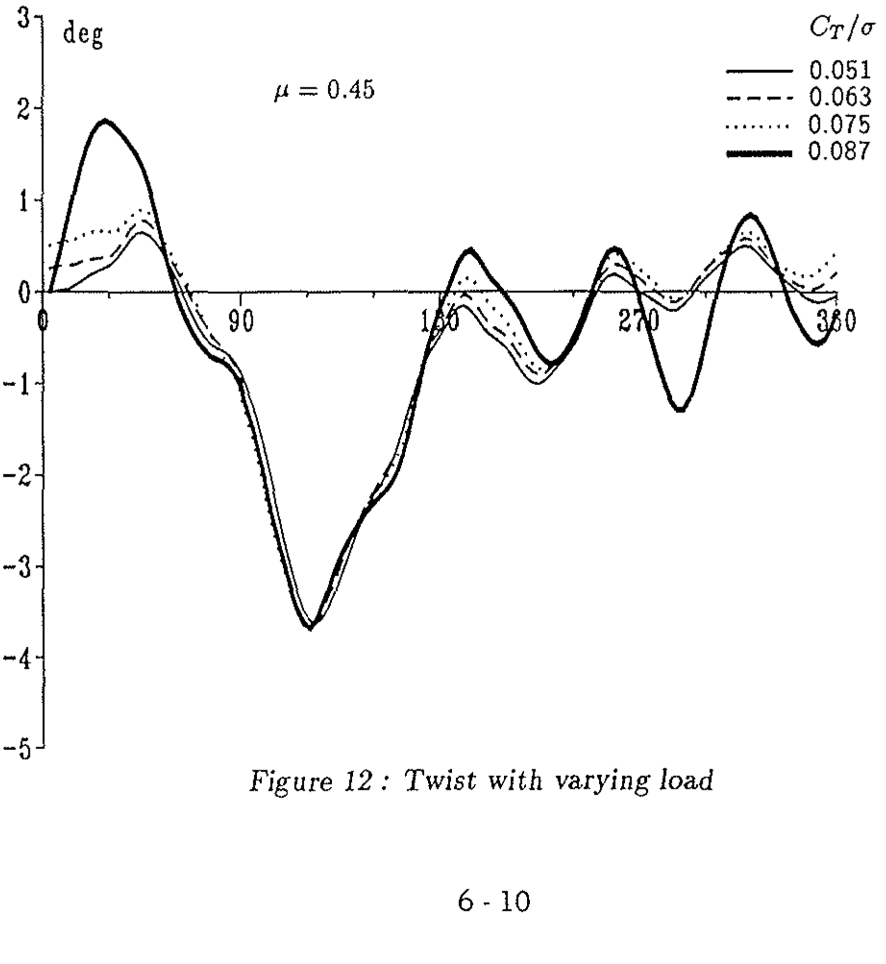



*Figure 12 : Twist with varying load*

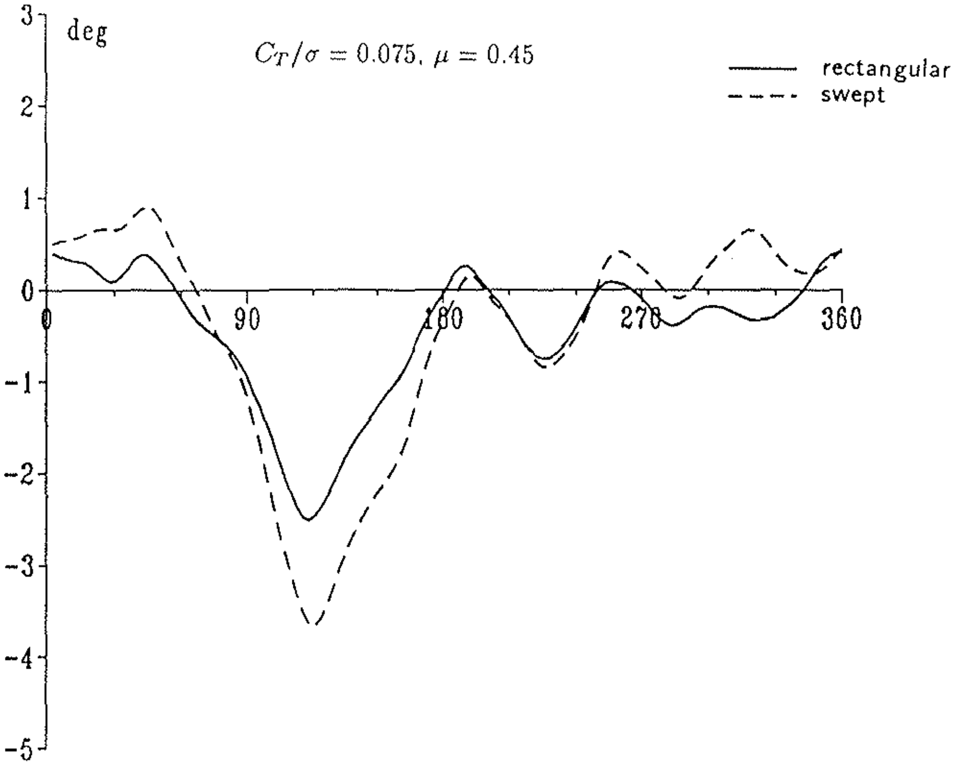



*Figure 13 : Blade tip shape effect on twist in forward flight*

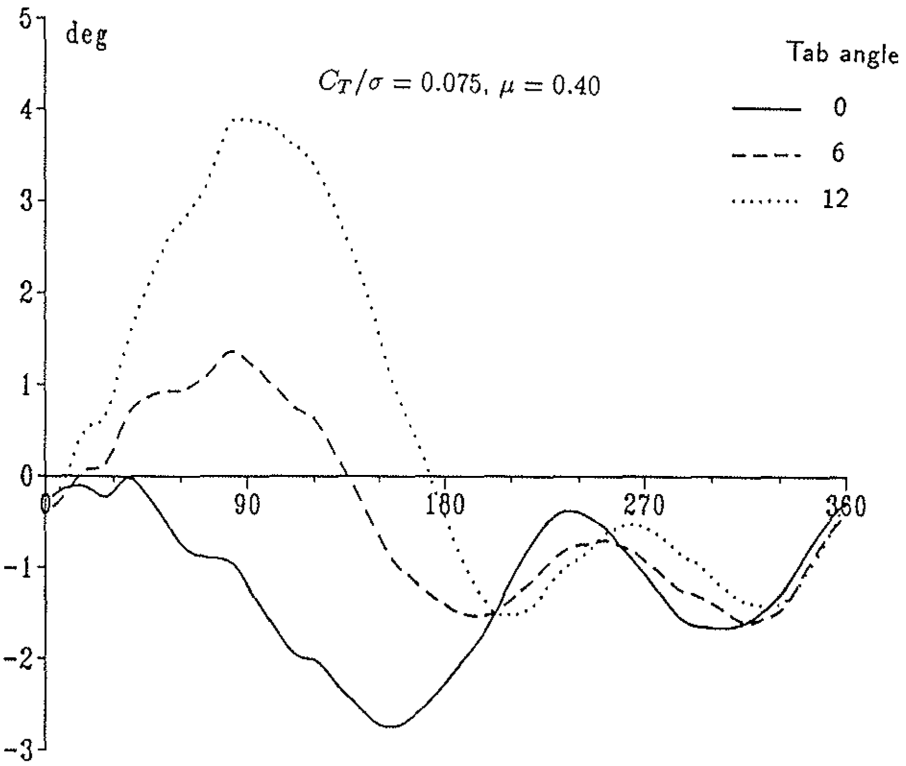



*Figure 14 : The effect of blade tab angle on twist*

$C_T/\sigma = 0.075, \mu = 0.40$

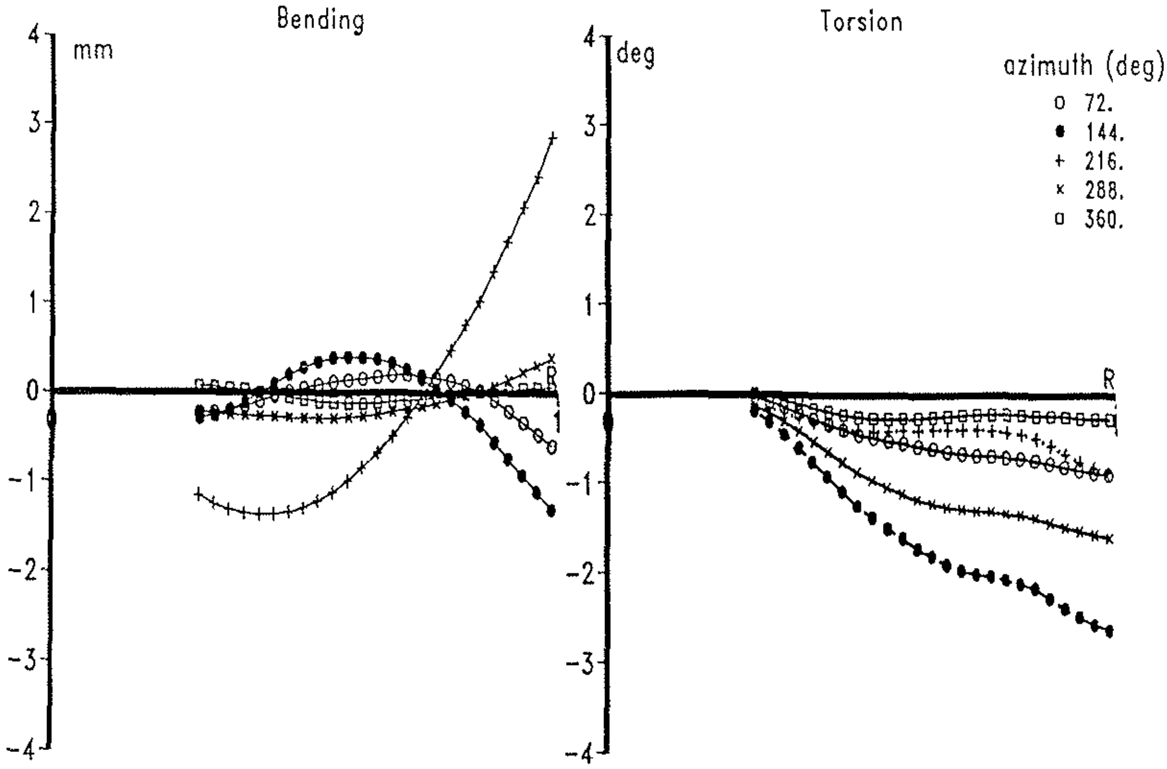



*Figure 15 : Typical spanwise bending displacements and twist angles*

# 5. Conclusion

The strain pattern analysis method for measuring blade deflections has now become a reliable tool. The gauge implementation necessary to clearly characterize the different calibration (modal) strain patterns is simple. Care must be taken that the calibration shape set (mode shapes) is obtained with end conditions that are as close as possible to real life.

A large set of deflection data has been obtained on rotor models in the wind tunnel. It is being used both for code validation and in physical analyses intended to give a better understanding of blade and rotor behaviour.

REFERENCES


1. D.R. Gaukroger and G.J.W. Hassal. Measurement of vibratory displacements of a rotating blade. *Vertica, 2,* 1978.
2. H. Loiseau and C.T. Tran. Structural deformation measurement with strain gauges. *ONERA internal document* 1981.