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# Twist control of airfoils using a “reactive” method

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## ABSTRACT

Active twist control of airfoils by means of embedded actuators has been widely studied during the last decade (N.A.S.A., University of Maryland, D.L.R., O.N.E.R.A., ...) Here, we propose a method which is to our knowledge new and which makes it possible to control the twist by modifications of the internal structure of the profile inducing displacement of the shear center and, therefore, modifications of the torsional moment and angle. This method is only operating if the profile is submitted to an external force. This is why this method is called “reactive” by opposition to the method mentioned above. Experiment has been done to verify the efficiency of the method proposed.

**Keywords:** torsion, twist, airfoil, control

## 1. INTRODUCTION

When an airfoil is embedded in an air flow, it is submitted to aerodynamic forces the resultants of which are mainly lift and drag forces. In any cross-section, the local density of these forces highly depends on the angle of attack of the airfoil.

In a first approximation, an airfoil may be considered as a rigid structure with a prescribed angle of attack. But, in order to optimize its aerodynamic performances, maximize its lift or minimize its drag for example, it is necessary to consider its deformations due to aerodynamic forces. In particular, the airfoil is subjected to both bending and torsional deformations. The torsional deformation has to be considered with care because it induces a change in the angle of attack and therefore changes in the local densities of lift and drag forces. The improvement of the aerodynamic performances does require a good knowledge and control of the twist of the airfoil.

Many papers found in the literature, in particular from N.A.S.A.<sup>1</sup> and University of Maryland<sup>2</sup> in U.S.A., D.L.R.<sup>3,4</sup> in Germany and O.N.E.R.A.<sup>5</sup> in France, show that a method currently developed for this purpose consists in inserting in the airfoil some actuators that make it possible to control the torsional deformation. Their action tends to increase or reduce the “natural” deformation of the structure. This method, named active control, is very effective but it has some limitations because it needs external energy proportional to the torsional energy relative to external forces which can be a high level of energy.

The method we propose to control the twist of the airfoil is, as far as we know, new. It consists in modifying the internal elastic equilibrium of the structure. These internal modifications induce variations of the torsional moment and therefore a variation of the twist angle. In order that these modifications could be effective, the airfoil has to be submitted to external forces. This is the reason why this method is called a “reactive” control method.

In order to obtain the internal equilibrium modifications, changes are made in the internal structure of the airfoil without any change in the aerodynamic profile and therefore in the aerodynamic center. These internal modifications which are not energy consuming induce a displacement of the shear center of the airfoil. The way they are done is to be patented. That is why we will not enter in the details of it. The torsional moment is therefore changed because the aerodynamic profile and center do not vary. As it is possible to modify the torsional moment, it is also possible to modify the twist angle and therefore the angle of attack, which is the

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objective. The question are, which is the amplitude of the modifications with respect to the twist angle induced by external forces? How to use them for twist control?

In order to check experimentally the potential of the proposed system, a first demonstrator has been designed for which the structural modifications were done by hand. A second demonstrator, also activated by hand, has been dedicated to the identification of the activation system. In particular, evaluations of the torsional characteristics, including the locations of the shear center resulting from the internal modifications, have been performed. A third demonstrator has been designed showing the possibility of remote activation. Simulations will show what will be done in the future on a final demonstrator to be designed using remote activation.

## 2. EXPERIMENTAL VERIFICATION : A FIRST DEMONSTRATOR

### 2.1 description

This demonstrator was built in order to have a first check of the ability of the system proposed and also of the order of magnitude of the modifications of the twist angle that can be obtained. It is a cantilever beam with span 500 mm, chord 100 mm and thickness 10 mm (fig. 1).

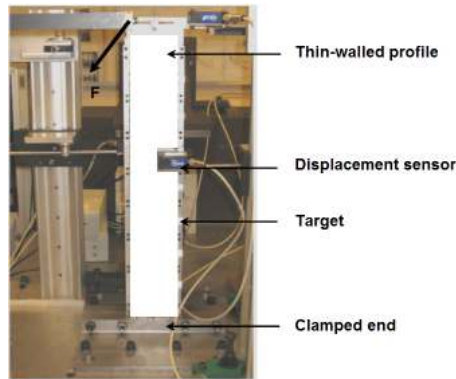


Figure 1. demonstrator 1

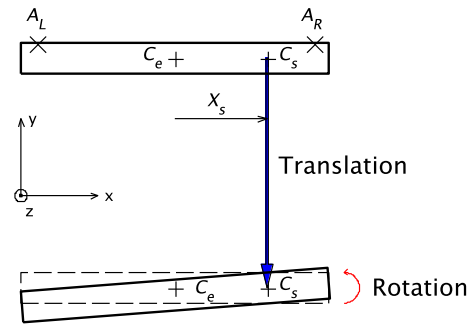


Figure 2. cross-section displacements

Its internal structure results from a complex assembling whose layout has been chosen in order to obtain a large displacement of the shear center, with respect to the chord size, when the internal system is activated. The structural modifications are done by hand in order to simplify the manufacturing of the internal system.

This demonstrator has been submitted to a transverse point-force applied at its free-end. This force induces bending and torsion of the beam, the deformations of which are determined by the measurement of displacements of selected cross-sections. Two sensors for each cross-section are required to separate flexural and torsional deformations.

According to the classical Euler-Bernoulli beam theory, the cross-sections are supposed to behave like rigid bodies. Their displacement are then completely determined by, for example, the displacement of the shear center ( $C_s$ ) and the rotation around it (fig. 2).

When the displacements  $V_L$  and  $V_R$  of, respectively, the left  $A_L$  and right  $A_R$  points are known, the twist angle  $\theta$  and the flexural deflection  $V_F$  read :

$$\begin{cases} \theta &= \frac{V_L - V_R}{2b} \\ V_F &= \frac{V_L + V_R}{2} - X_s \cdot \theta = \frac{V_L}{2} \cdot \left(1 - \frac{X_s}{b}\right) + \frac{V_R}{2} \cdot \left(1 + \frac{X_s}{b}\right) \end{cases} \quad (1)$$

where  $2b$  is the distance between left  $A_L$  and right  $A_R$  points,  $C_e$  the elastic center and  $X_s$  the algebraic distance between  $C_s$  and  $C_e$  ( $X_s = \overline{C_e C_s} \cdot \vec{e}_x$ ).

More precisely, when a cantilever beam (length  $L$ ) is submitted to a transverse force  $F$  acting at a point  $A$  of its free-end, the torsional angle reads:

$$\theta = \frac{M_T}{G \cdot J_T} \cdot L \quad (2)$$

where  $M_T$  is the torsional moment and  $G \cdot J_T / L$  the torsional stiffness of the beam. The torsional moment is the moment of the external forces calculated at the shear center  $C_s$  of the beam.

$$M_T = (\vec{F} \times \overrightarrow{AC_s}) \cdot \vec{e}_z \quad (3)$$

In particular, when the transversal force is acting at  $C_s$ , the torsional moment and the rotation vanish.

## 2.2 experimental results

A first test is relative to the determination of the displacement of the shear center when the internal system is activated. Its displacement is about 30 mm on the righthand or lefthand side of the elastic center which is to be compared with the chord dimension ( $\sim 100$  mm).

A second test is relative to the global behaviour of the structure when it is loaded by a flexure-torsion force. Using the relations (1), deflections and twist angles along the demonstrator can be plotted and compared with predictions which are usually a third-degree polynom and a straight line. The theoretical curves are fitted with the experimental data (fig. 3). Therefore, in spite of a complex internal assembly, the structure behaves like a beam and it is always the case whichever modifications of the internal structure are performed.

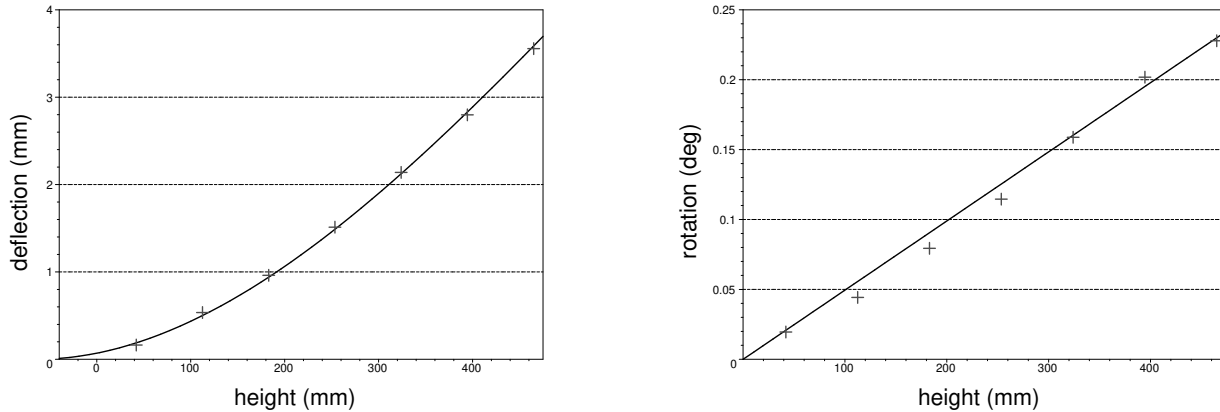


Figure 3. deflection and rotation of the beam

A third test gives an order of magnitude of the modifications of the twist angle. For example, let us apply a point-force at 20% of the free-end chord simulating an aerodynamic force and measure the twist angle at this free-end. When the internal system is not activated, this angle is  $0.09^\circ$ . When the system is activated, it can vary between the ranges  $0.35^\circ$  and  $-0.17^\circ$ .

In conclusion, these results show the potential of the method proposed. It is possible to induce variations of the twist angle of the order of the static twist angle in a cantilever beam.

### 3. EXPERIMENTAL VERIFICATION : A SECOND DEMONSTRATOR

#### 3.1 description

This second demonstrator looks like an elementary part of the first demonstrator, making it possible to study more precisely the internal activation system. The internal modifications are still done by hand. In spite of its short length (250 mm) with respect to its width (100 mm) and height (60 mm) (fig. 4), this demonstrator is supposed to be a cantilever beam. A point-force load  $F$  can be apply at the free-end and the deflection and twist angle are measured.

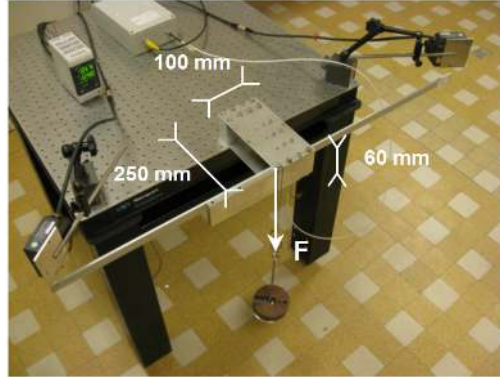


Figure 4. an elementary twist control system enclosed in a box

In order to control the twist angle, there is a need for a measurable parameter which can be related to this angle. The values of such a parameter would make it possible to estimate the variation of the twist angle induced by the activation system and so allow for open or closed loop control. Fortunately, the activation system proposed does possess such a parameter.

#### 3.2 rotation and internal parameter versus increasing applied force

A first experiment has been performed using a point-force increasing from 0 to  $F$  then decreasing from  $F$  to 0. During this loading, the rotation and internal parameter were measured (fig. 5). Two states of the system were considered: a so-called natural state and a state for which the activation system is on. In each case, the rotation and internal parameter depends linearly on the force. The unloading path doesn't show any hysteresis of the system (fig. 5).

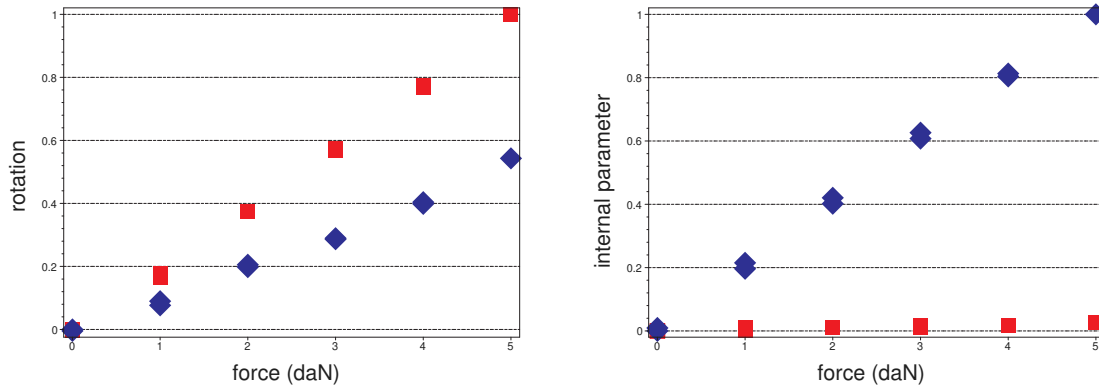


Figure 5. rotation and internal parameter while loading and unloading: with (◆) or without (■) internal modifications

It is to be remarked that the slope of the rotation versus force curves is not the torsional stiffness of the beam. The slope of the internal parameter versus force depends on the state of the activation system. But, for a fixed state, it is linear.

### 3.3 torsional characteristics

The torsional characteristics that will be considered are the location of the shear center and the torsional stiffness. Three states of the activation system were considered corresponding to the extremal and average locations of the shear center. For each of these states, the rotation has been measured when applying a point-force at two different points  $A_L$  and  $A_R$ ,  $A_L$  on the left handside ( $-37.5$  mm with respect to the location 0 mm) and  $A_R$  on the right handside ( $+37.5$  mm with respect to the location 0 mm). The results can be read on fig. 6.

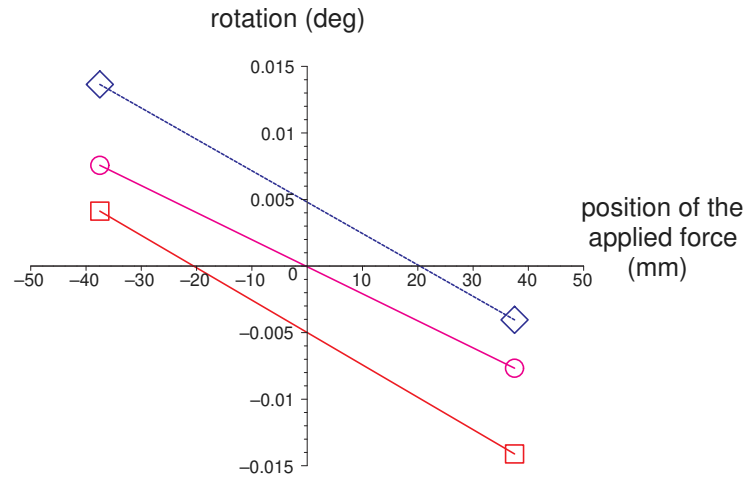


Figure 6. determination of the torsional characteristics

Fig. 6 shows three straight lines. The intersection between these lines and the x-axis are related to the location of the shear centers which can vary from  $-20$  mm to  $+20$  mm apart from location 0 mm which is the average location and corresponds to the so-called natural state. The slopes of the straight lines are related to the torsional stiffness. It appears that the variation of this stiffness is less than 20%. It is to be remarked that the torsional stiffness is less affected by the internal modifications than the location of the shear center.

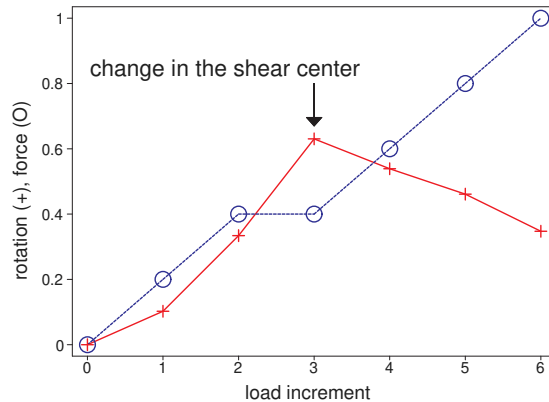


Figure 7. example of load sequence

In order to illustrate the influence of the modification of the shear center during loading, the following experiment has been performed. The system is initially in its natural state, the shear center is at location 0 mm. A force is applied by increments at a point with location  $+10$  mm. For the two first increments of load, the rotation vary from 0 to 0.4 (fig. 7). For the third increment, the load remains constant. Then, the internal system is activated inducing a gap in the rotation due to the imperfections of the hand activated system. The shear center is then the point with location  $+20$  mm. For the increments 4, 5, 6 of the load, there is a decrease of the rotation from 0.6 to 0.4 which shows that the torsional moment is now negative which is what we were looking for!

### 3.4 rotation and internal parameter versus complex loading

When the internal equilibrium of the structure is changing, there is not only a modification of the twist angle but also a variation of the internal parameter which can be measured. In order to analyse more precisely the relation between this parameter and the rotation, another experiment has been done. As before, a point-load is applied at the free-end. Four steps are performed:

- 1) increase of the force from 0 to a transition force  $F_1$
- 2) internal activation with force  $F_1$  applied
- 3) increase of the force from  $F_1$  to  $F_2$
- 4) decrease of the force from  $F_2$  to 0.

After the internal modification have been done, the slope in the rotation (fig. 8) and the internal parameter (fig. 9) become different. This experiment has been done several times with the same transition force  $F_1$  and maximum force  $F_2$ . The results are always close. This experiment has also been done with different transition force  $F_1$  and the same maximum force  $F_2$ . The results always show the same pattern. It has been noticed that when the force  $F_1$  was modified, the rotation  $\theta_{max}(F_1)$  at maximum constant force  $F_2$  do vary. This rotation as a function of the value of the internal parameter at maximum force  $F_1$  has been plotted (fig. 10). The dependance of  $\theta_{max}$  versus internal parameter is linear. This parameter seems to be quite suitable for twist control.

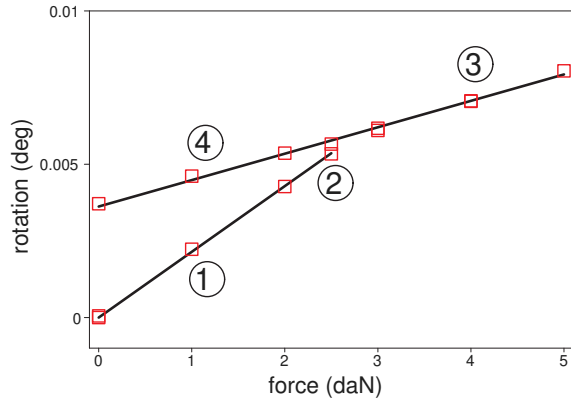


Figure 8. rotation

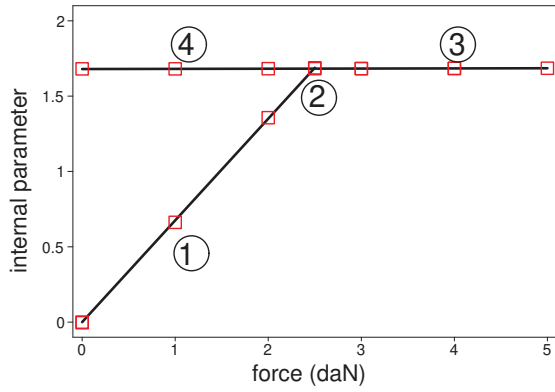


Figure 9. internal parameter

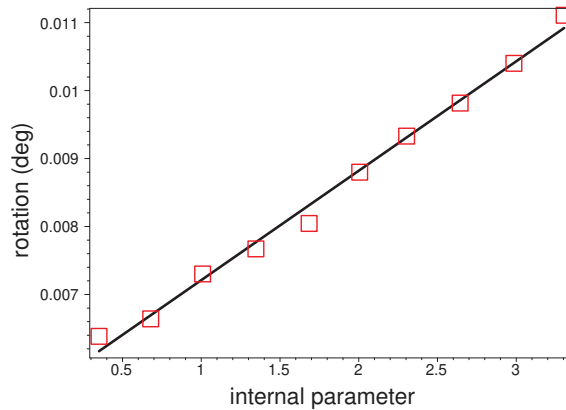


Figure 10. relation between rotation and internal parameter

## 4. REMOTE ACTIVATION

We speak about remote activation to distinguish it from hand made activation as mention above. In fact, this remote activation means that the activation of the system is done from the outside of the demonstrator with an automated process.

### 4.1 control method

In order to test the possibility of remote activation, a third demonstrator has been designed with a more elaborated activation system which will be used in the future for open or closed loop control studies. This demonstrator has the same in-plane dimensions as the second one but a smaller thickness (20 mm) (fig. 11). With this demonstrator, it is possible to shift the shear center by  $\pm 10$  mm with respect to the natural state.

Only simple tests have been performed. For example, figure 12 shows the results of one of these tests, i.e. the rotation versus the applied force. For this one, the demonstrator is, as usual, submitted at its free-end to a point-force. Three steps have been performed:

- 1) increase of the force from 0 to a maximum force  $F_1$
- 2) internal activation with force  $F_1$  applied
- 3) decrease of the force from  $F_1$  to 0.

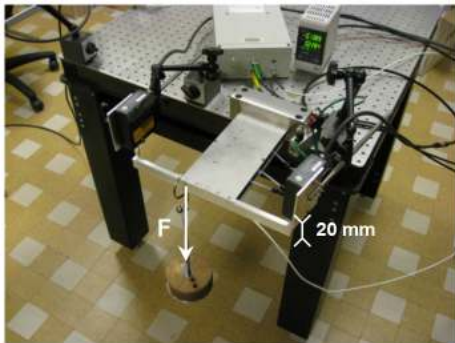


Figure 11. an elementary twist control system with remote activation

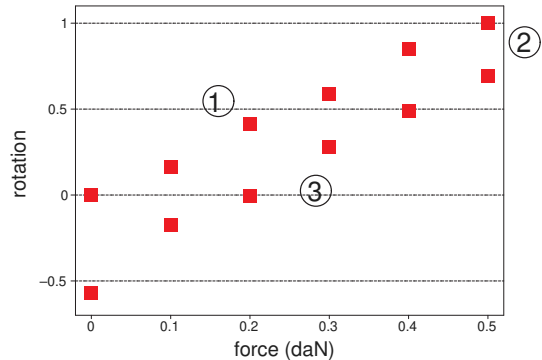


Figure 12. a simple test

In step 1 (fig. 12), the demonstrator is in its natural state and achieves the rotation  $\theta_1$  at the maximum force  $F_1$ . In step 2, the activation system is activated with the constant force  $F_1$  applied. Then the location of the shear center moves and there is a modification in the rotation from  $\theta_1$  to  $\theta_2 = \theta_1 - \Delta\theta$ . In step 3, the location of the shear center remains unchanged. When the force vanishes, it remains a residual rotation due to pre-stresses in the internal activation system. It is also to be remarked that the slope of the rotation versus force is not the same as in step 1.

This remote activation of the demonstrator could make it possible to control the rotation between the values  $\theta_1$  and  $\theta_2$ . In order to illustrate the method used to do so, other simple experiments have been performed.

It appears that the simplest way of activating the system is to proceed by increments. For example, starting from the natural state, the system is activated during a time step  $\Delta t$  and then deactivated. The system returns then to the natural state. Two examples of the results of such an incremental activation can be found on figures 13 and 14.

On figure 13 is shown the evolution of the rotation during a first loading. From 0 to 1, there is no force applied and therefore no rotation. From 1 to 2, a point-force of about 1 daN is applied inducing a rotation  $\theta_2$ . Then, the force remains unchanged from 2 to 5. From 3 and 4, an incremental activation of the system is performed resulting in a return of the rotation to 0. It is to be remarked that the activation system makes it possible to remove the rotation deformation. For an aerodynamic profile, submitted to a permanent flow, it looks as if the profile be rigid (has not been deformed in torsion by the flow).



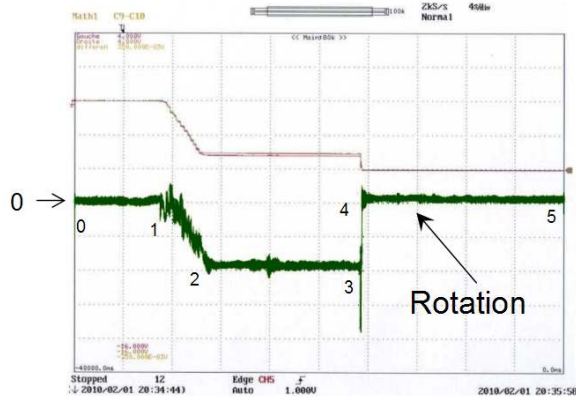


Figure 13. example 1: one increment

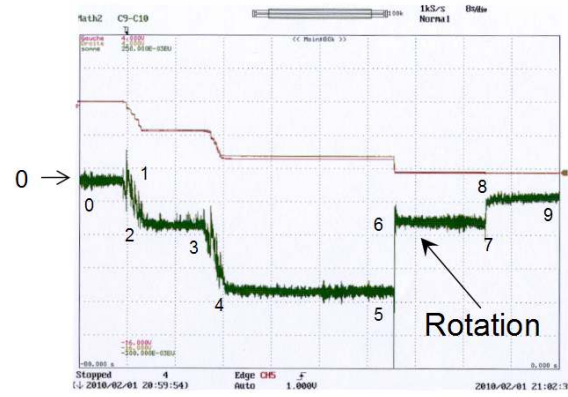


Figure 14. example 2: two increments

On figure 14 is shown the evolution of the rotation during a second loading. From 0 to 1, there is no force applied and therefore no rotation. From 1 to 2, a point-force of about 1 daN is applied inducing a rotation  $\theta_2$ . From 2 to 3, the force and rotation remain unchanged. From 3 to 4, a 2 daN force is applied inducing an increase in the rotation from  $\theta_2$  to  $\theta_4$ . Then, the force remains unchanged from 4 to 9. From 5 to 6, an incremental activation of the system is performed resulting in a decrease of the rotation to  $\theta_6 < \theta_4$ . From 7 to 8, another increment is performed, the rotation becoming  $\theta_8 < \theta_6$ . It is to be remarked that the rotation  $\theta_8$  is not 0. In the previous experiment, the duration of the increment of activation had the correct duration to allow the rotation to return to 0. In the second one, two increments were performed without obtaining a return to 0 of the rotation. An optimization of the duration of the increments will be necessary to obtain prescribed residual rotations.

We expect that the monitoring of the internal parameter will make it possible to control the twist using an open loop or quasi-open loop control, the system being incrementally activated. This will be part of a future work.

Remark: the system is considered to be in its natural state when the activation system is off; it is possible that an activation previous to the return to the so called natural state induces in the system pre-stresses; nonetheless this possible pre-stress state is referred as the natural state which is not strictly true.

## 4.2 simulations

The behaviour of the beam and activated system has been modeled from the experimental results. The equations of motion for torsion then reads:

$$M \frac{d^2\theta}{dt^2} + C \frac{d\theta}{dt} + K\theta = m_T(t) + m_P(t) \quad (4)$$

where  $M$ ,  $C$  and  $K$  are the ad-hoc inertia, damping and stiffness terms,  $m_T(t)$  is the applied torsional moment and  $m_P(t)$  the torsional moment resulting from the pre-stresses generated in the activation system by the activation process.

To illustrate what we intend to do in future work, we have done two simulations for which the transient terms are neglected. The results of these simulations are plotted on figures 15 and 16. They correspond to a modelisation of demonstrator 2 with a point-force applied at its free-end according to the following scheme:

- 1) the force is applied gradually from 0 to  $F_1 = 1$  between 0 and 1''
- 2) the force is maintained at level  $F_1$  from 1'' to 2''
- 3) the force is decreased gradually from 2'' to 3''
- 4) no force is applied from 3'' to 4''

The evolution of the rotation follows the following scheme:

- a) the system is in its natural state from 0 to 2
  - 1) the rotation increases gradually from 0 to  $\theta_1 = 1/2$  between 0 and 1''
  - 2) the rotation remains equal to  $\theta_1$  from 1 to 2
- b) the activation system is on from 2 to 3
  - 3) the rotation is decreased from  $\theta_1$  to 0 from 2 to 3, the force remaining equal to  $F_1$
- b) the system is in its natural state from 3 to 5
  - 4) the rotation decreases from 0 to  $-\theta_1$  from 3 to 4, whilst the force is decreased from  $F_1$  to 0
  - 5) the rotation remains equal to  $-\theta_1$  from 4 to 5, though the applied force is 0

the activation system is then pre-stressed
- c) the activation system is on from 5 to 6
  - 6) the rotation is "decreased" from  $-\theta_1$  to 0
- d) the system is in its natural state from 6 to 7: no force applied, no rotation, no pre-stresses.

Fig. 15 is relative to a continuous activation of the system whilst fig. 16 is relative to an incremental one. The continuous activation is purely theoretical, the incremental one will be use in practice in future work. It is to be remarked that the incremental activation gives results very close to the continuous activation ones. There is a small difference near points 3 and 6. When the incremental process is used, it is not possible to make the rotation come back exactly to 0.

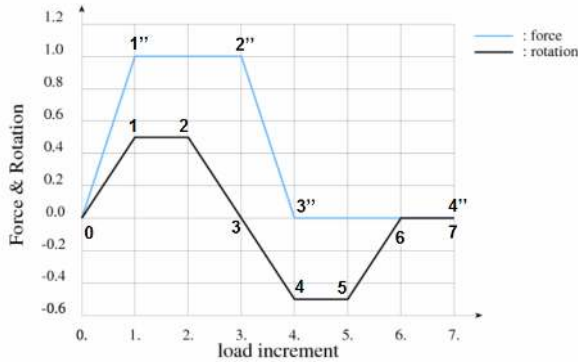


Figure 15. simulation with a continuous activation

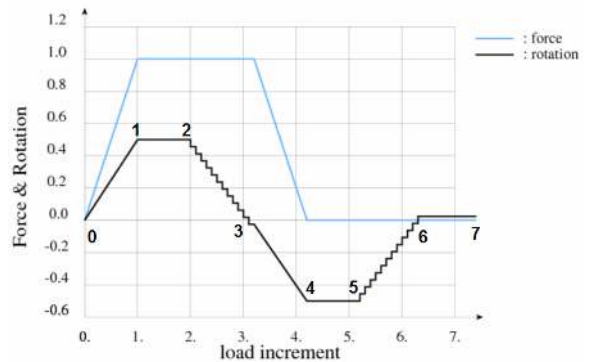


Figure 16. simulation with an incremental activation

## 5. CONCLUSION

The experimental results presented above show the ability of the system proposed to induce large modifications in the location of the shear center of cantilever beams by remote activation with only small modifications in the torsional stiffness. An internal parameter, correlated with the rotation, is attached to the activation system and may be measured, providing a way to estimate experimentally the modification of the rotation induced by shifts in the shear center.

An incremental way of activating the system has been proposed and experimentally checked. Simulations using a mechanical model of demonstrator 2, updated from experimental results, show that this incremental process is very close to a theoretical continuous one.

Future work will be about a full demonstrator of a cantilever beam profile. Simulations will be done to define scenarios of control in various situations (static and dynamic in the very low frequency range). Control laws will be derived. Experimental control will be performed on the full demonstrator and comparisons with simulation will be done.

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