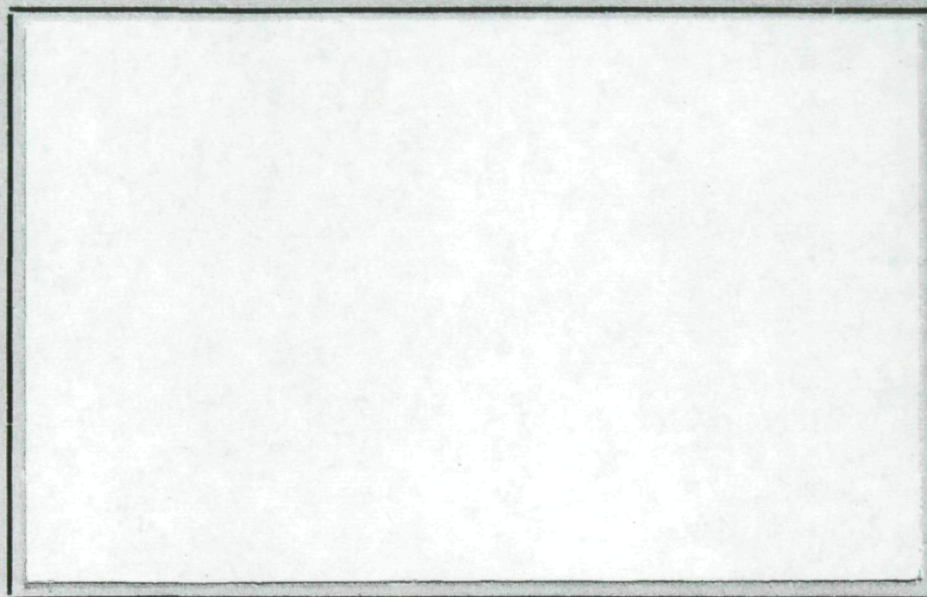


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FLUTTER SUPPRESSION AND GUST ALLEVIATION  
USING ACTIVE CONTROLS

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## 1. Introduction

The investigation reported herein is a follow-up of some previous studies (refs. 1,2) which relates to the application of the Aerodynamic Energy approach to problems of Flutter Suppression and Gust Alleviation. The following three aspects of the problem are dealt with here:

a) The use of a <sup>2 2</sup> leading and trailing edge (L.E. - T.E.) activated strip to control the pitch of the aircraft: The need for such an investigation is pointed out in ref. 2 where it is shown that a normal activation of a L.E.-T.E. strip along the horizontal-tail leads to a considerable loss in the longitudinal static stability of the aircraft. A simple modification of the control-law is suggested here which permits achieving the required control.

b) The possible replacement of the L.E.-T.E. activated strip by a T.E.-Tab strip: The motivation for such an investigation originated from work done at NASA-Langley where an activated L.E.-T.E. strip was mechanized to suppress flutter and then tested in the Transonic Dynamics Tunnel (ref. 3). It is felt that the problems associated with the mechanization of the L.E. control are somewhat more difficult than those associated with the T.E. control and that the T.E.-Tab combination might offer a simpler solution to the problem.

c) Study of the parameters affecting the performance of the activated L.E.-T.E. strip for two specific aircraft: The parameters tested are strip location, control-law gains and a variation in the control law itself. The investigation includes the Arava Stol Transport and the Westwind Executive Jet Transport, and is intended to correct, expand, explain, and improve the results reported in ref. 2 in terms of the potential of Active Controls to

suppress flutter and alleviate gust loads.

Additional details relating to the above-mentioned studies are briefly presented in the following sections.

## 2. Pitch Control Using a L.E.-T.E. Activated Strip

It has been pointed out (ref. 1) that the two-dimensional control law, derived through the use of the Aerodynamic Energy concept, activates the controls in such a way as to counteract any lift build-up on the strip and to provide large damping forces. This reduction in lift build-up eventually leads to both a reduction in the bending moments, acting on the wing and in the reduction of accelerations sensed at the center of gravity (c.g.) of the aircraft (ref. 2). However, when placing the activated strip on the horizontal tail of the aircraft, the resulting reduction in the lift build-up due to a rigid body pitch-motion, clearly reduces the effectiveness of the horizontal tail and thus leads to a deterioration in the longitudinal static stability of the aircraft. To counteract these detrimental effects on the static stability, the following control law is suggested:

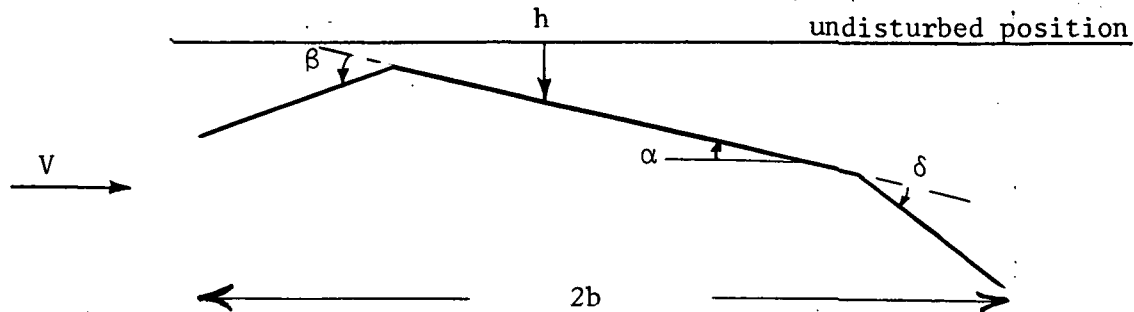
$$\begin{Bmatrix} \beta \\ \delta \end{Bmatrix} = [C] \begin{Bmatrix} \bar{h}/b \\ \bar{\alpha} \end{Bmatrix} + \frac{1}{\omega_r} [G] \begin{Bmatrix} \dot{\bar{h}}/b \\ \dot{\bar{\alpha}} \end{Bmatrix} \quad (1)$$

where

$$\left. \begin{aligned} \bar{h} &= h - h_r \\ \bar{\alpha} &= \alpha - \alpha_r \end{aligned} \right\} \quad (2)$$

The (controlling) matrices [C] and [G] are clearly of order 2x2.  $\omega_r$  is a reference frequency which is normally varied as an additional "gain"

parameter. The notation for  $\beta$ ,  $\delta$ ,  $\alpha$ ,  $h$  and  $b$  is explained in the following sketch



The values of  $h$  and  $\alpha$  at a reference section are denoted in Equation (2) as  $h_r$  and  $\alpha_r$ , and the dots denote derivatives with respect to time (i.e.,  $\dot{h}$  and  $\dot{\alpha}$ ). The difference between the control law suggested in Equation (1) and the one previously used (ref. 1, 2) lies in the introduction of the relative values of  $\bar{h}$ ,  $\bar{\alpha}$  (and their derivatives) instead of  $h$  and  $\alpha$ .

Let us now choose the c.g. section of the aircraft as the reference section. This means that a simple rigid-body pitch movement will lead to  $\bar{\alpha} = 0$  and thus neutralize the activation of the control due to rigid body pitch. The gain associated with  $\bar{h}$  is zero whereas the gains associated with  $\dot{\bar{h}}$  and  $\dot{\bar{\alpha}}$  lead to dissipative forces which introduce some sluggishness into the pitch movement of the aircraft with no subsequent degradation in the static stability. For horizontal tail flutter problems, the movement of the c.g. of the aircraft is generally unimportant in controlling the instability, and the activated strip should maintain its effectiveness since the elastic deformations are fully maintained in  $\bar{h}$ ,  $\bar{\alpha}$  (and their derivatives). However, when no pitch control is required, tail flutter may best be tackled by taking the root section of the horizontal tail as the reference section.

The suggested control law was applied to both the Arava and the Westwind aircraft, and the results obtained confirm the expectations regarding the static stability. Mention should be made here that the application of the unmodified control law on both the Arava and the Westwind led to a very severe static longitudinal instability. It is therefore believed that control laws of the type suggested by Equation (1) will open a variety of possibilities relating to flutter suppression and gust alleviation problems. Some of the results obtained here will be mentioned in a later section.

### 3. The Possible Use of a T.E.-Tab Active Controls for Flutter Suppression and Gust Alleviation

It has already been mentioned that the L.E. control presents some control problems since it carries relatively large aerodynamic hinge moments, and since it is inherently unstable in the absence of control forces. An alternative control surface which could replace the L.E. control and yet retain both the stability characteristics (and hinge moment levels) and the flutter suppression power of the trailing-edge control could be of great help. In the following, the combination of T.E.-Tab control surfaces is investigated in an attempt to determine both the effectiveness of the system and the values of the control parameters which insure best performance.

Preliminary considerations lead to the choice of a 20% chord T.E. control and 8% chord tab control. The results obtained through an optimization process similar to the one described in ref. 1 yield the following values for the optimum (within the constrained limits) control parameters relating to sensor information regarding the movement of the 30% chord point

$$[C]_{\text{opt}} = \begin{pmatrix} 0 & -1.7 \\ 0 & 0 \end{pmatrix}$$

$$[G]_{\text{opt}} = \begin{pmatrix} 0.5 & -1.0 \\ 0 & 2.0 \end{pmatrix}$$

where the control law is given by

$$\begin{pmatrix} \delta \\ \gamma \end{pmatrix} = [C] \begin{pmatrix} h/b \\ \alpha \end{pmatrix} + i [G] \begin{pmatrix} h/b \\ \alpha \end{pmatrix}$$

and where  $\gamma$  is the tab rotation. The maximum value of  $\lambda_{\text{min}}$ , appropriate for  $\frac{V}{\omega b} = 78$ . ( $\sim 1200$ ), is about  $\frac{2}{3}$  of the value corresponding to the L.E.-T.E. system (where the corresponding value of  $\lambda_{\text{min}} \sim 1800$ ). The value of  $\lambda_{\text{min}}$  can further be increased by multiplying  $[G]$  by a positive constant larger than unity.

Sensitivity to off design values around the optimum is made for each  $C_{ij}$  by  $G_{ij}$  parameter. Only one example of such a variation is shown here (fig. 1).

It can thus be seen that the described T.E.-Tab control system has the capability of suppressing flutter. A study of the optimized deflection values (through the control law) shows that much smaller control torques will be required to drive not only the tab control but also the T.E. control. This leads to a substantial alleviation in actuator requirements.

#### 4. Study of the Parameters Affecting the Performance of L.E.-T.E. Control Systems

The initial aim of this investigation was confined to the completion of the work reported in ref. 2. It was, however, found that the values quoted in ref. 2 for the control surface deflection were erroneous in that the control surfaces experienced, in effect, considerably larger rotations. This finding leads to some serious questions regarding the practical effectiveness of the control system since the range of control surface rotations is clearly limited in actual flights. It is therefore apparent that some changes have to be introduced into the control law so as to increase the effectiveness (per unit rotation of the control surfaces) of the L.E.-T.E. system. This investigation yields some interesting results as described in the foregoing sections.

##### 4.1 A Modified Control-Law for Wing Sections

A careful inspection of the results reported in ref. 2 indicates the existence of a problem area at the outer part of the wing, around the mid-span and the wing-tip regions. In these regions the following can be observed:-

- a) A substantial decrease in the maximum positive value of the bending moment due to gusts is always accompanied by an equally substantial decrease in the maximum negative value of the bending moment so that (as for the case of the Westwind) the absolute value of the maximum bending-moment is often larger with activated controls as compared to the unactivated aircraft.
- b) The effect of active control systems located at the outer wing area on the c.g. accelerations is relatively small.



The present investigation reveals the following additional points relating to the outer wing area:-

c) The control surface deflections must assume very large values in order to become modestly effective even within the limitations indicated in section (a) above.

d) The effectiveness of the control surface deflection (defined to be the ratio between the control surface deflection  $\delta_c$  at the time when either the bending moment (B.M.) or the c.g. acceleration assumes maximum values and the maximum control surface deflection  $\delta_{max}$ , i.e.  $\delta_c/\delta_{max}$ ) is small in all cases, moving around the order of 0.5 for  $\delta$  and smaller values for  $\beta$ .

e) A success in reducing the B.M. level at a specific time interval often leads to large increases in B.M. at subsequent time intervals.

It thus appears that some irrational elements exist in the application of the control law at the outer wing region - a region which is naturally accepted to be best suited for both B.M. alleviation and flutter suppression. A breakdown of the control rotation into different elementary contributions indicates that this problem originates from the contributions of the rigid body movements of the aircraft to the control surface rotations and from the response of the structure to those rotations. Therefore a control law which enables the reduction of those contributions might prove to be superior. This can be achieved by the following control law

$$\begin{aligned} \begin{Bmatrix} \beta \\ \delta \end{Bmatrix} &= [C] \begin{Bmatrix} \bar{h}/b \\ \bar{\alpha} \end{Bmatrix} + \frac{1}{\omega_r} [G] \begin{Bmatrix} \dot{\bar{h}}/b \\ \dot{\bar{\alpha}} \end{Bmatrix} + \\ &+ [C] \begin{Bmatrix} h_r/b \\ \alpha_r \end{Bmatrix} + \frac{1}{\omega_{r2}} [G] \begin{Bmatrix} \dot{h}_r/b \\ \dot{\alpha}_r \end{Bmatrix} \end{aligned} \quad (3)$$

The first two elements of Equation (3) control the relative motion of the wing and are similar to Equation (1) whereas the last two elements control the reference section movement (i.e. the c.g.). Using Equation (2), Equation (3) reduces to

$$\begin{Bmatrix} \beta \\ \delta \end{Bmatrix} = [C] \begin{Bmatrix} h/b \\ \alpha \end{Bmatrix} + \frac{1}{\omega_r} [G] \begin{Bmatrix} \dot{h}/b \\ \dot{\alpha} \end{Bmatrix} + \frac{1}{\omega_{r_2}} [G] \begin{Bmatrix} \dot{h}_r/b \\ \dot{\alpha}_r \end{Bmatrix} \quad (4)$$

For simplicity, the root section was chosen as the reference section for control systems located along the wing.

Some general stability considerations indicate that stability will generally be maintained provided

$$\omega_{r_2} > \omega_r \quad (5)$$

clearly, if

$$\omega_{r_2} = \omega_r$$

then Equation (4) reduces to the unmodified control law.

The modified control law was applied to both the Arava and Westwind aircraft leading to drastic improvements in both the activated strip performance and its effectiveness. This improvement is apparent when studying figs. 2 - 5 which relate to the Westwind. They show the results of the application of a (1-cos) gust using the unmodified control law (figs. 2, 3) together with those obtained when using the modified law (figs. 4, 5). It is believed that improvement in results can also be obtained for control laws based on other concepts, by a similar extension of the changes introduced herein.

#### 4.2 Non Linear Effects of the Gust Response with Active Controls

It has already been mentioned in a previous section, that the effectiveness of the control surface is a very important parameter. We desire it to be as close to unity as possible so that the control deflection is utilized in full at the appropriate time to alleviate the gust loads. To get some insight into this problem a (1-cos) gust is applied to the aircraft following the FAR regulations at  $V_c$ . The value of  $\omega_r$  is varied keeping all the remaining parameters of the control law constant. It can be shown that  $\beta$  and  $\delta$  are proportional to  $V_G/V$  where  $V_G$  is the gust velocity and  $V$  is the flight speed. Hence for a linear behaviour of the maximum deflection  $\delta_{\max}$  with the control deflection  $\delta_c$  at the critical time (i.e. the deflection when either the B.M. or the c.g. acceleration assumes maximum value), the plot of  $\delta_c/\delta_{\max}$  vs  $\delta_c/V_G$  should yield a straight line parallel to the  $\delta_c/V_G$  axis. Fig. 6 shows a different behaviour - the control surface effectiveness

increases with  $\delta_c/V_G$ . This means that if we allow the maximum deflection of the control surface (at a specified location along the wing and at some specified flight conditions) to double its value, the resulting alleviation, which is proportional to  $\delta_c$ , will increase by a larger factor. To illustrate this point, consider point A in fig. 6. This point corresponds to

$\frac{\delta_{\max}}{V_G/V} = -4.88$  and  $\frac{\delta_c}{V_G/V} = -2$ . The point designated as point B corresponds to  $\frac{\delta_{\max}}{V_G/V} = -9.76$ , and  $\frac{\delta_c}{V_G/V} = -9.3$ . In passing from point A to point B we allow

$\frac{\delta_{\max}}{V_G/V}$  to double its value, and in so doing,  $\frac{\delta_c}{V_G/V}$  increases by the factor

4.65. Since the reduction in B.M.<sub>max</sub> is approximately linear with  $\frac{\delta_c}{V_G/V}$

(fig. 7), the B.M.<sub>max</sub> alleviation increases from 23% (at point A) to 61% (at point B).

It can be similarly stated that for the same value of  $\delta_c$ , the effectiveness  $\delta_c/\delta_{max}$  increases as  $V_G/V$  decreases. These important results can be formulated in the following alternative manner:

a) Two control surfaces at adjoining locations along the wing can be considered as equivalent to a single control surface at either of the two locations having a value of  $\delta_c/\frac{V_G}{V}$  which equals the sum of the two  $\delta_c/\frac{V_G}{V}$  values of the two control surfaces.

b) On the basis of (a) above and the aforementioned illustration, it becomes apparent that two adjoining control surfaces have an alleviation power which is much larger than the sum of their separate effects.

c) Since the control system effectiveness is dependent on  $\delta_c/\frac{V_G}{V}$ , the changing of  $V_G/V$  leads to changes in  $\delta_c/\frac{V_G}{V}$  which in turn affect  $\delta_c/\delta_{max}$  in a fashion already discussed. Therefore, if we assume for example, that  $V$  is reduced while  $V_G$  is maintained constant, then it follows that the effectiveness of the system is reduced due to the reduction in  $\delta_c/\frac{V_G}{V}$ .

The above dependence of the control effectiveness on  $\delta_c/\frac{V_G}{V}$  leads us to believe that slower aircraft, subjected to relatively large values of  $V_G/V$ , will eventually prove to be less effective in gust alleviation than faster aircraft. Hence, a comparison between the Arava, which is a slow aircraft ( $V_c = 85$  m/sec), and the Westwind ( $V_c = 260$  m/sec) which is a relatively fast one is of special interest.

The results of the computer runs obtained so far confirm the above conclusions. At the present stage, processing of the many results is taking

place. These will shortly be summarized. It may however be stated that large reductions in gust loads (B.M. and c.g. accelerations) with large increases in flutter speed can be obtained within the feasible range of control surface deflections.

#### 4.3 Effect of Pitch Control

The results obtained so far indicate that the pitch control by itself is relatively ineffective as a gust alleviation device. Its effectiveness is manifested when high pitch rates have to be suppressed. However, these reductions in pitch rates lead to a slow-down in the wing B.M. relief (which follows the stabilizing changes in the angle of attack of the aircraft) and thus degrade the B.M. alleviation of the aircraft. Caution must therefore be exerted when introducing pitch control to avoid too large a damping force due to pitch.

Mention should also be made here that the reduction in pitch rates is normally accompanied by a reduction in control surface rotations along the wing - this is clearly in addition to the reduction in the acceleration levels along the fuselage at stations distant from the c.g.

#### 5. Future Research Program

It is planned, upon the completion of the present stage of the investigation, to perform a continuous gust analysis which will use atmospheric turbulence inputs and also introduce elements of real control characteristics. It is also believed, that an investigation into the flutter and gust characteristics of some additional aircraft of different types, such as a very large

transport (like the B-52) and a fighter type aircraft will provide a reasonably balanced picture regarding the potential of active controls as flutter suppression and gust alleviation devices.

## 6. References

- [1] Nissim, E.: Flutter Suppression Using Active Controls Based on the Concept of Aerodynamic Energy, NASA TN D-6199, March 1971.
- [2] Nissim, E.: Flutter Suppression and Gust Alleviation Using Active Controls, TAE Report 198, Technion - Israel Institute of Technology, March 1974.
- [3] Sandford, M.C.; Abel, I.; Gray, D.L.: A Transonic Study of Active Flutter Suppression Based on an Aerodynamic Energy Concept, AIAA/ASME/SAE 15th Structures, Structural Dynamics and Materials Conference, Paper No. 74-403, April 17-19, 1974.

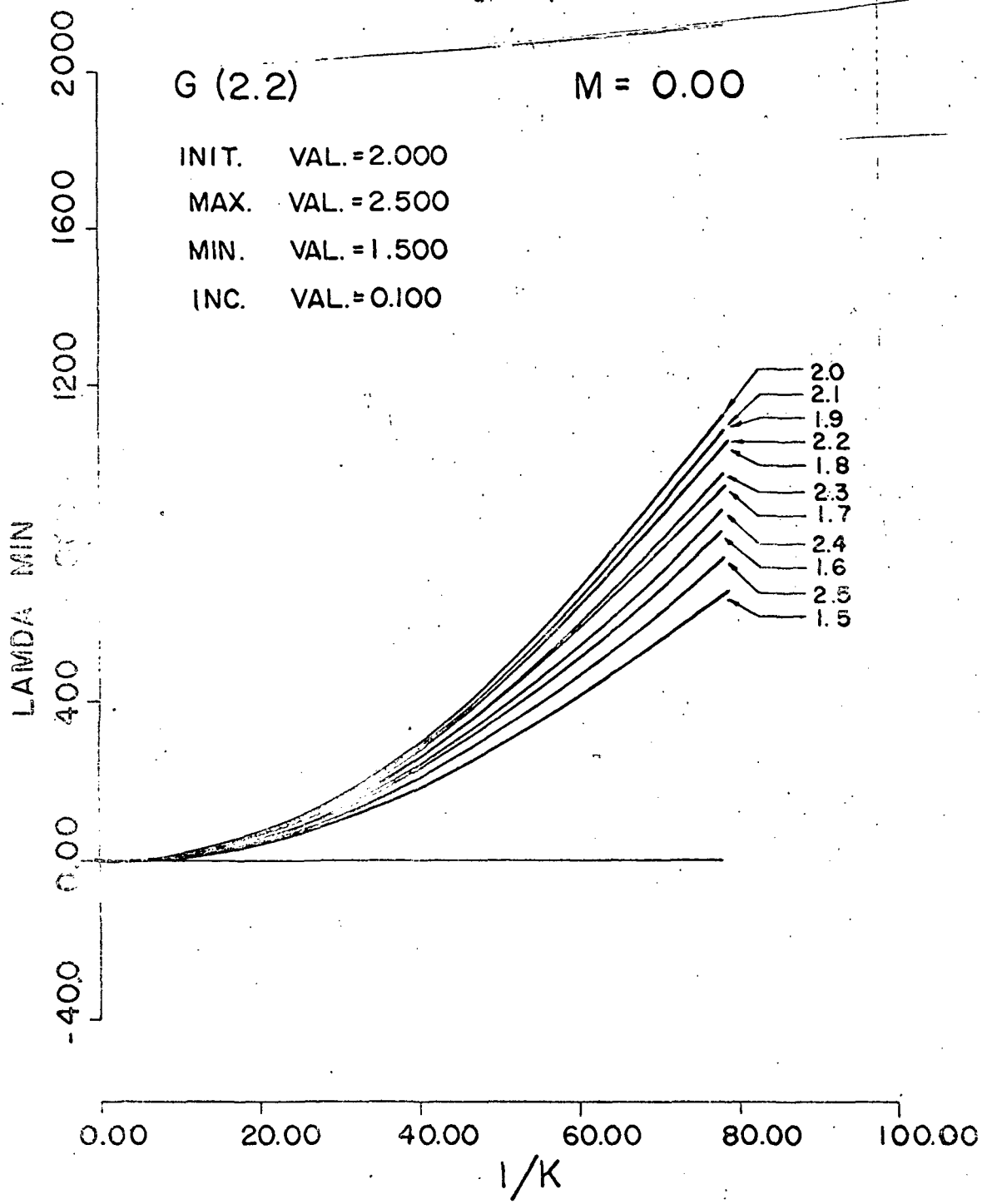


Figure 1 : Variation of  $\lambda_{MIN}$  around optimum with G(2,2) - T.E.-Tab control system

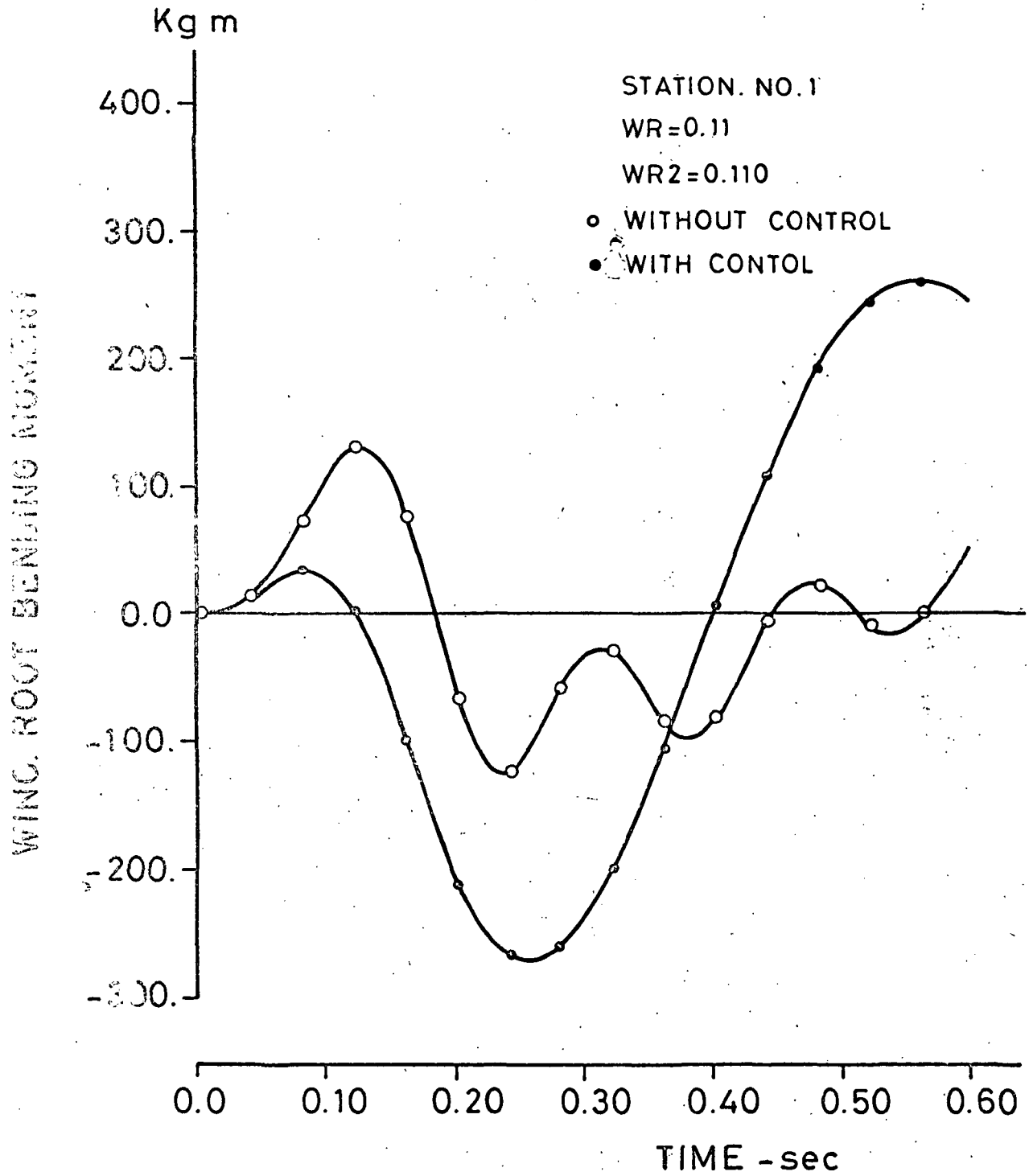


Figure 2: Variation with time of the maximum wing bending moment (at the wing root) due to a (1-cos) upgust - Westwind transport with a single L.E.-T.E. active system located at the tip of the wing and driven by the unmodified control law.



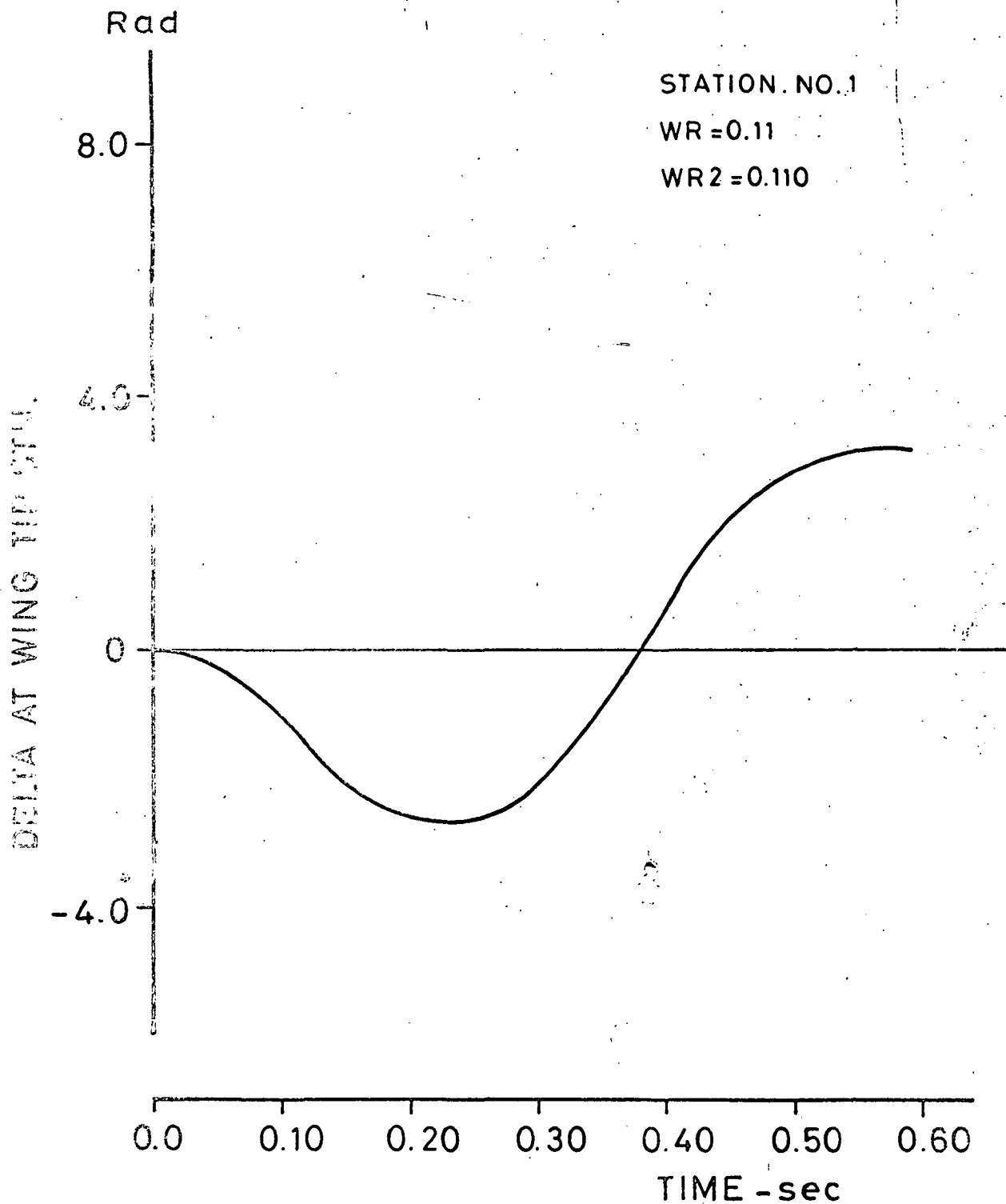


Figure 3: Variation with time of the T.E. control rotation due to a (1-cos) upgust - Westwind transport with a single L.E.-T.E. active system located at the tip of the wing and driven by the unmodified control law.

Fig 4

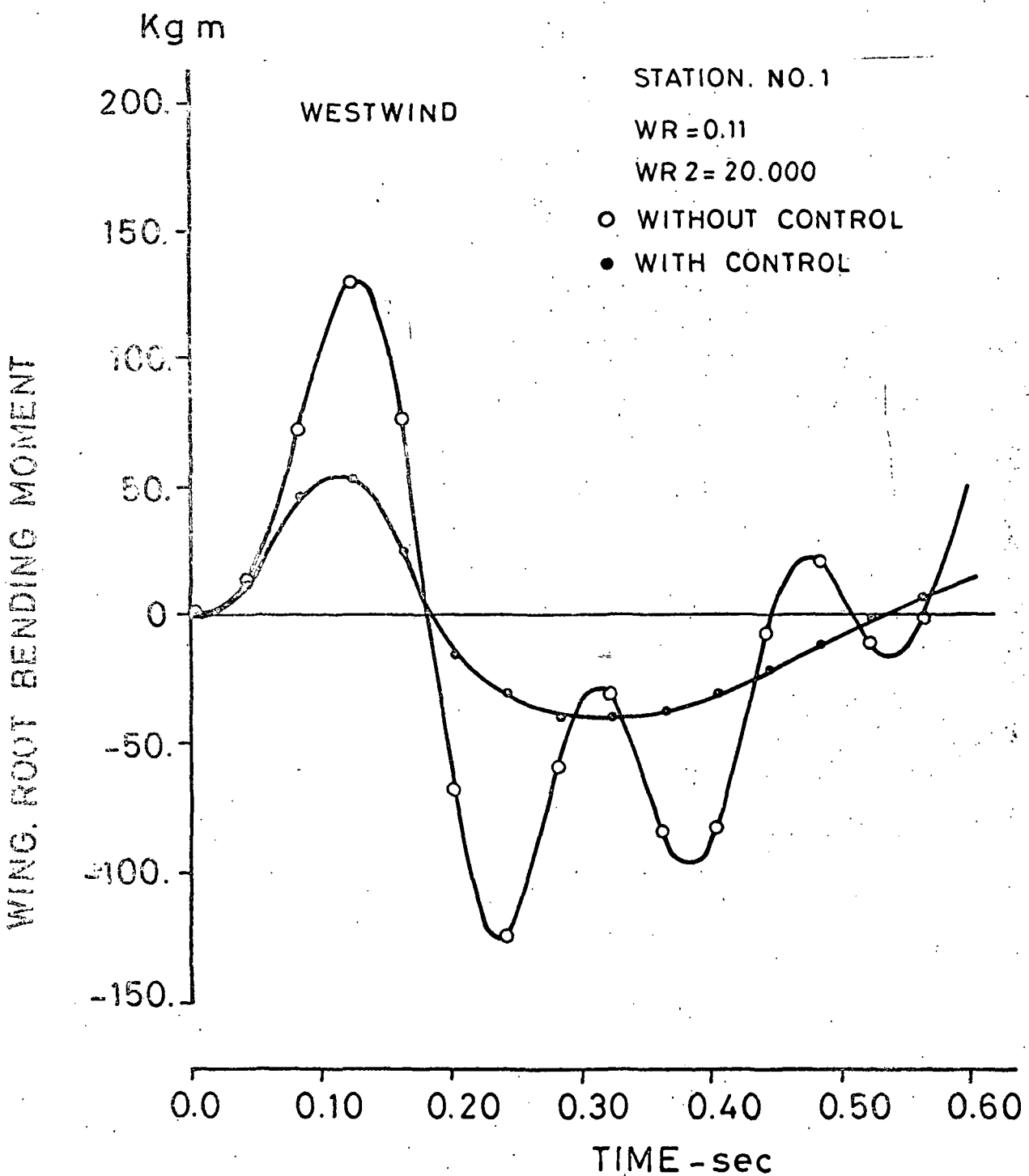


Figure 4: Variation with time of the maximum wing bending moment (at the wing root) due to a  $(1-\cos)$  upgust - Westwind transport with a single L.E.-T.E. active system located at the tip of the wing and driven by the modified control law.

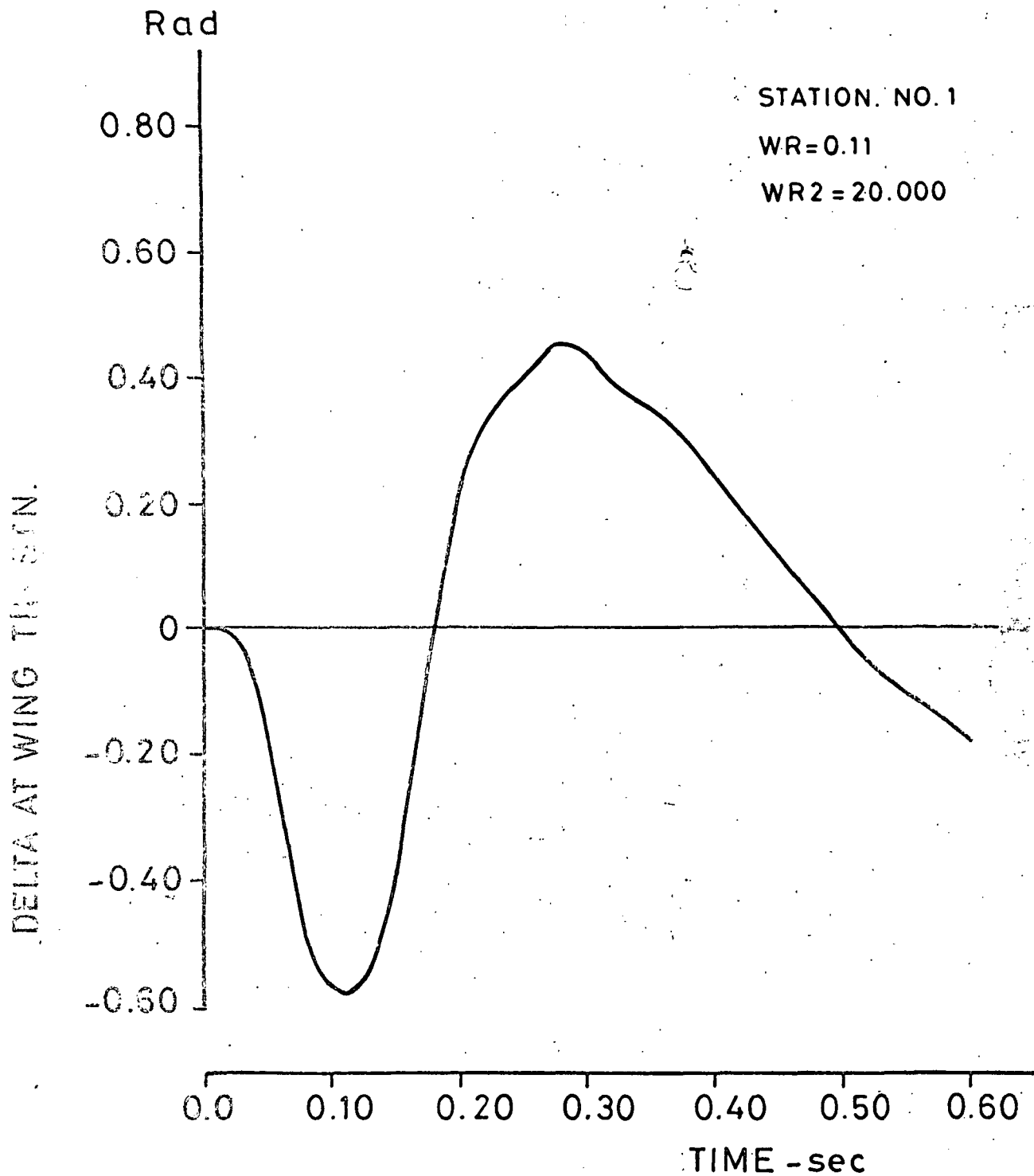


Figure 5: Variation with time of the T.E. control rotation due to a (1-cos) upgust - Westwind transport with a single L.E.-T.E. active system located at the tip of the wing and driven by the modified control law.

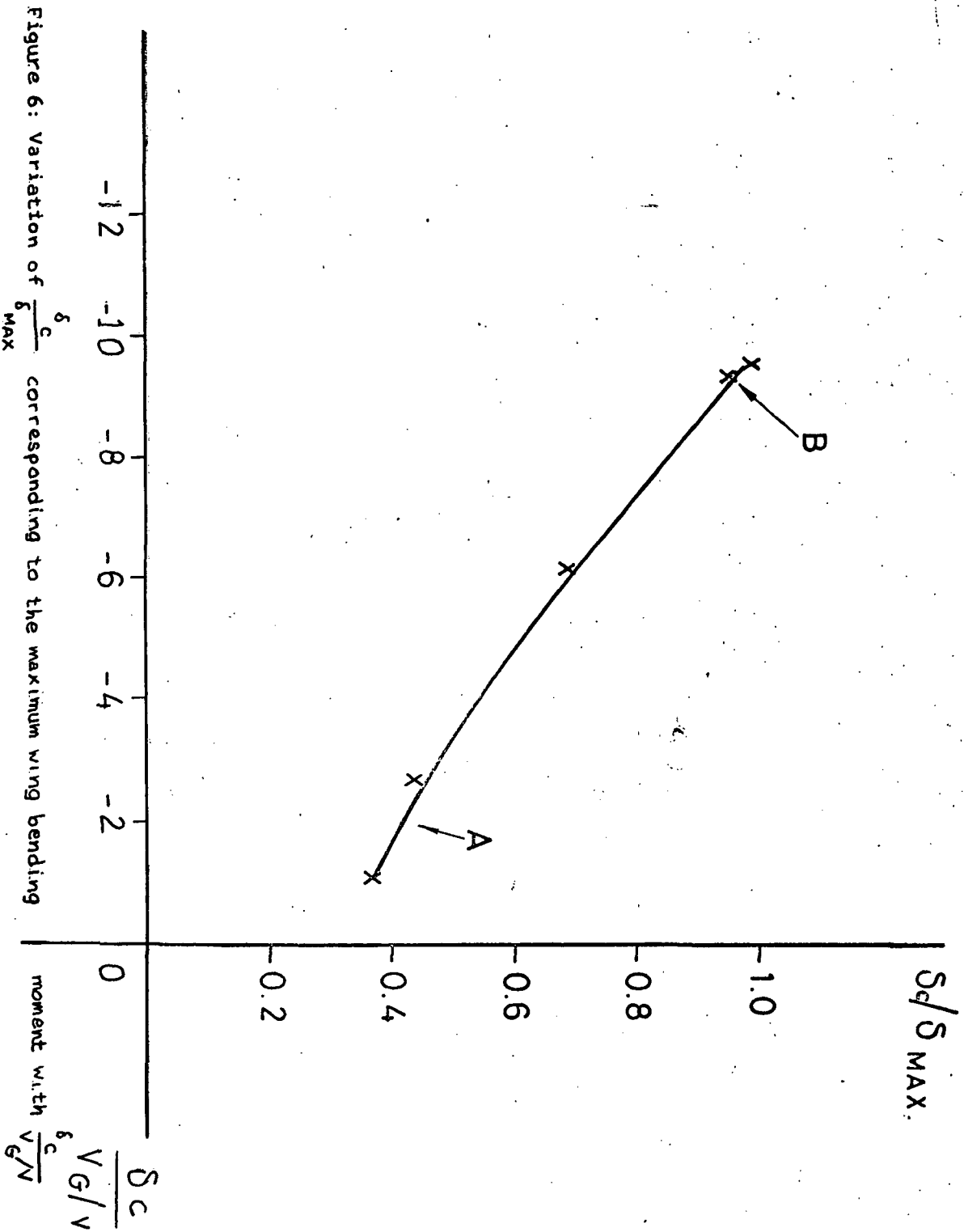


Figure 6: Variation of  $\frac{\delta c}{\delta c_{MAX}}$  corresponding to the maximum wing bending moment with  $\frac{\delta c}{Vg/V}$  due to a (1-cos) upgust - westwind transport with a single T.E.-T.E. active system located at the tip of the wing and driven by the modified control law.

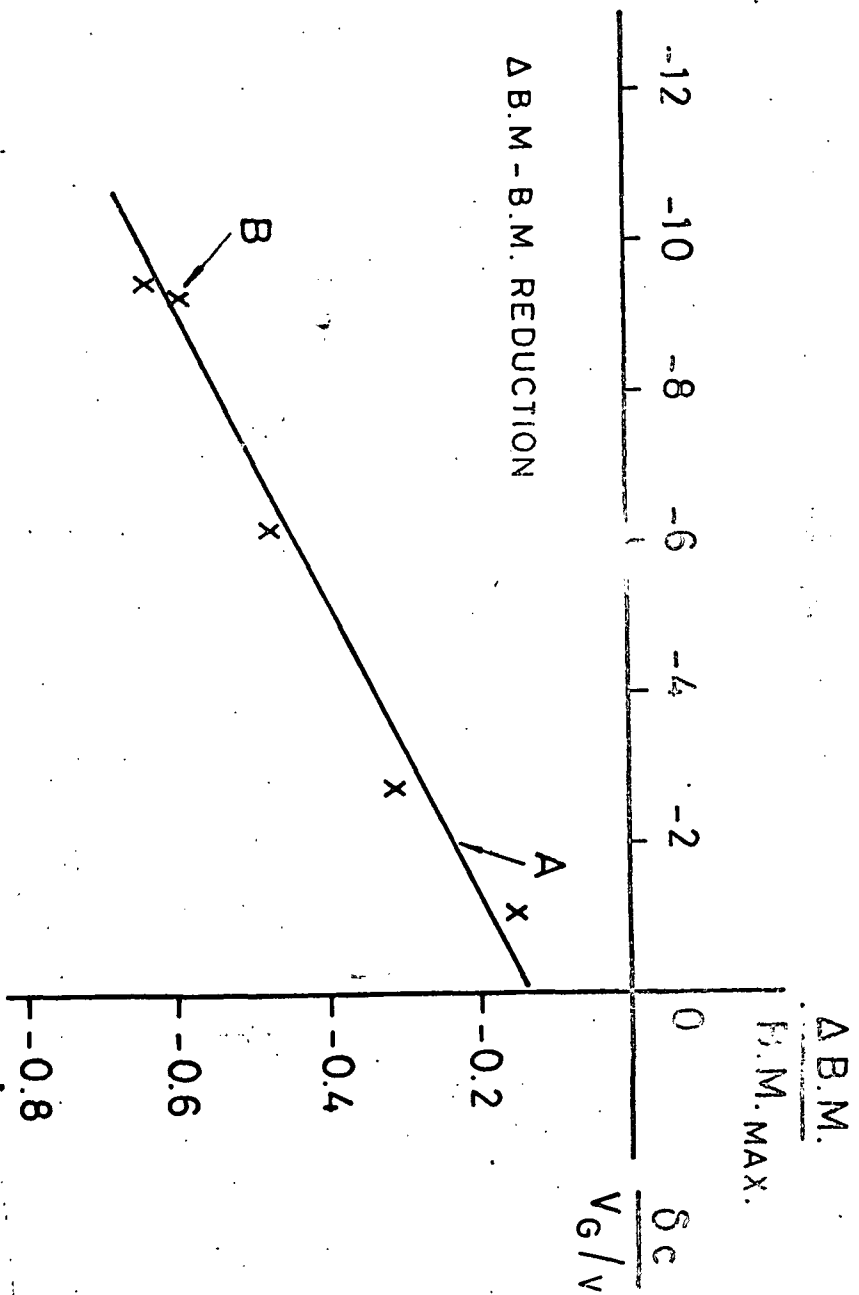


Figure 7: Variation of the maximum wing bending moment reduction with  $\frac{\delta c}{Vg/v}$  due to a (I-cos) upgust - Westwind transport with a single I.E.-T.E. active system located at the tip of the wing and driven by the modified control law.