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(ORGANISATION DU TRAITE DE L'ATLANTIQUE NORD)

SYMPOSIUM ON UNSTEADY AERODYNAMICS FOR AEROELASTIC ANALYSES OF INTERFERING SURFACES

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FOREWORD

A Symposium on Unsteady Aerodynamics for Aeroelastic Analyses of Interfering Surfaces was organized by the Structures and Materials Panel of AGARD in conjunction with its 31st meeting in Tønsberg, Norway, in November 1970. It was attended by approximately 60 participants from ten nations. The papers given on this occasion have been collected in the two volumes ~~which I have the honour of presenting to the scientific audience of NATO.~~

One of the major concerns of the Structures and Materials Panel is the development of analytical and practical methods for predicting, preventing and controlling aeroelastic problems affecting both aircraft and aerospace-craft. Whether flutter, gust response, or alleviation and mode stabilization system designs are concerned, the development of safe and efficient methods depends on the ability to predict unsteady aerodynamic forces accurately.

HGR.

As early as 1964, a Working Group created within The Structures and Materials Panel for the purpose of studying these forces, defined a small number of wing planforms to be used as standard models for comparing aerodynamic force prediction methods on the basis of data on vibration modes, excitation frequencies and Mach numbers. In view of the tremendous utility of such a scheme, the Panel decided in 1968 to extend this programme to include the interaction of more complex aerofoils such as T-tails or wing horizontal tail combinations. Several planforms, as well as some parameters, have been recently selected to be used as standards for comparisons.

Consequently, the objectives and themes of the Symposium have been set as follows:

(a) Present and discuss the latest contributions to methods for predicting unsteady aerodynamic forces in the interactions of lifting surfaces.

(b) Determine the merits and limitations of various methods.

(c) Present applications and numerical values which can be employed to evaluate the new methods proposed.

(d) Formulate suggestions about future developments and requirements.

The papers presented have been arranged in five sections:

I. Methods using the lifting surface equation.

II. Methods using a lattice or lifting lines.

III. Application to the calculation of unsteady interaction forces.

IV. Testing and application to flutter.

V. Wing-control surface interactions.

In view of their general scope, four of these papers have been selected by the Panel as contributions to the Manual on Aeroelasticity (in six volumes), published by AGARD on the initiative of the Panel. These four papers, the titles of which are listed below, have been collected in Part I of the Conference Proceedings in order to be included in the Manual:

– H.ASHLEY	"Some Considerations Relative to the Prediction of Unsteady Airloads of Interfering Surfaces (Introductory Paper)" – to be included in Volume II, Chapter 1.
– D.E.DAVIES	"Calculation Methods for Unsteady Airforces on Tandem Surfaces and T-tails in Subsonic Flow" – to be included in Volume II, Chapter 3.
– R.DAT and Y.AKAMATSU	"Representation of a Wing by Lifting Lines. Application to the Calculation of the Interaction of Two Wings in Tandem" – to be included in Volume II, Chapter 3.
– D.L.WOODCOCK and E.YORK	"A Supersonic Box Collocation Method for the Calculation of Unsteady Airforces on Tandem Surfaces" – to be included in Volume II, Chapter 5.

The other eleven papers have been collected in Part II of the Conference Proceedings. While these are also of great interest, either they have already been published elsewhere for their major part, or the discussions which followed them revealed some divergences of an experimental nature bringing out the existence of many yet unsolved problems. Surely the usefulness and value of such a meeting lies precisely in this: to provide specialists of entirely different origins and training with the opportunity of discussing together a fundamental problem in constant development and, thus, of evaluating the progress made so far and that still to be accomplished.

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PRESSURE MEASUREMENTS ON AN HARMONICALLY OSCILLATING SWEPT WING WITH TWO CONTROL SURFACES IN INCOMPRESSIBLE FLOW

by

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SUMMARY

The results of an experimental study of the pressure singularities occurring along the control surface edges of a harmonically oscillating swept wing-control surface system in incompressible flow are presented and discussed. The two control surfaces ranged along the whole span of the wing and could be excited so that alternatively the inner or the outer flap or even both were oscillating with different phases and amplitudes relative to each other and relative to the wing.

NOTATIONS

x,y	[m]	Cartesian coordinates, see Figure 1
Λ		aspect ratio of the model $= b^2/F$
b	[m]	effective span $= 2\,s$
s	[m]	effective half-span, see Figure 1
l	[m]	constant model chord parallel to the flow direction
F	[m^2]	effective wing area $= 2\,l\,s$
ϕ		sweep angle
ω	[s^{-1}]	circular frequency
ω^*		reduced frequency, see Eq. (1)
l_R	[m]	constant chord of the control surfaces parallel to the flow direction
V	[$m\ s^{-1}$]	wind tunnel flow velocity
q	[$kg\ m^{-1} s^{-2}$]	dynamic pressure $= \frac{\rho}{2} V^2$
ρ	[$kg\ m^{-3}$]	air density
p	[$kg\ m^{-1} s^{-2}$]	unsteady pressure amplitude
Δc_p		non-dimensional pressure amplitude, see Eq. (2)
$\Delta c'_p$		real part of Δc_p
$\Delta c''_p$		imaginary part of Δc_p
A_W		angular rotation amplitude of the wing, positive nose-up
$A_{i.f.}$		angular rotation amplitude of the inner flap
$A_{o.f.}$		angular rotation amplitude of the outer flap
x_0	[m]	x-coordinate of the wing leading edge, see Figure 1
ξ		non-dimensional coordinate in chord direction $= (x - x_0)/l$
η		non-dimensional coordinate in span direction $= y/s$

PRESSURE MEASUREMENTS ON AN HARMONICALLY OSCILLATING SWEPT WING WITH TWO CONTROL SURFACES IN INCOMPRESSIBLE FLOW

H.Försching, H.Triebstein and J.Wagener

1. INTRODUCTION

In the kernel-function approach to the oscillating lifting surface problem for subsonic flow it is attempted to solve the relating two-dimensional integral equation by assuming that the unknown lift distribution can be expressed as a linear combination of properly selected loading functions with free coefficients. Then these unknown coefficients in the lift distribution are determined by satisfying the boundary conditions for prescribed normal velocity on the surface in some approximate manner, for instance through collocation or least-squares techniques[1,2,3,4]. In order to obtain satisfying numerical results with as few terms as possible it is of importance that the preselected loading functions represent the true pressure as closely as possible. In particular it is important that these functions have the same type of singular behavior near wing and control surface leading edges as the true one. If this is not the case one knows from comparing measurements that the approximate solutions will give inaccurate results near the edges. This holds specially true if a control point is selected too close to an edge, what may result in large over-all errors.

However, in the linearized formulation of the oscillating-surface problem, singularities in the lift distribution not only occur at subsonic leading edges and at control surface leading edges, but in general wherever the downwash prescribed by the deformation mode shapes of the oscillating wing is discontinuous. Such discontinuities also appear at the side edges of control surfaces, if the latter are vibrating with different amplitudes relative to the wing and relative to each other.

Actually it is a problem of considerable mathematical difficulty to find pressure loading functions which are satisfying all these singularities. The series of loading functions proposed and used so far in the kernel-function approach are mainly chosen to have a chordwise loading similar to the two-dimensional one with the wellknown square-root singularity at the wing leading edge and a spanwise loading of the type encountered in lifting line theory. With this type of loading functions, however, the presence of a control surface can only be included either by refining the network of collocation points and artificially smoothing the downwash discontinuities along the control surface edges, taking into account a large number of functions. More rigorously, the discontinuities in downwash at the control surface edges can be taken into account by adding the resulting proper logarithmic singularities along the control surface edges to the pressure loading series, as recently suggested by M. Landahl[5].

Very few numerical results of kernel-function calculations incorporating control surfaces have been published. They are generally confined to fullspan controls, and still less is known about the actual pressure distribution and the pressure singularities occurring with oscillating multi-control lifting surface systems. The present paper presents a systematic experimental study of the pressure singularities due to control surface motion. For this purpose unsteady pressure measurements on a harmonically oscillating swept wing with two control surfaces in incompressible flow have been carried out at various modes of vibration.

2. MODEL AND TEST SET-UP

The multi-control lifting surface system used for the experimental investigations is schematically illustrated in Figure 1. The fiber-glass reinforced halfspan plastics model consists of a swept wing with constant chord $l = 0.6$ m and with two control surfaces, termed henceforth the inner and outer flap. The wing had a symmetric NACA 0012 profile with a sweep angle $\phi = 25°$ and an aspect ratio $\Lambda = 2.94$. The constant chord l_R of the flaps amounted to 30% of the wing chord; the wing span was $s = 0.88$ m.

In three chordwise sections I, II and III parallel to the flow direction, in two additional sections IIa and IIb immediately near the inner side edge of the two flaps, and in two spanwise sections IV and V parallel to the control surface leading edges 94 pressure measuring points were arranged. As it is seen from Figure 1 there is an accumulation of these measuring points near the leading and the side edges of the control surfaces and the leading edge of the wing as well in order to enable a reasonable good measurement of the pressure distribution and the pressure singularities occurring along these edges. The measuring method applied was essentially that one suggested and worked out by H Bergh[6] and his co-workers at N.L.R. Amsterdam. The wing could perform rigid body rotation oscillations about an axis normal to the airflow as indicated in Figure 1. Similarly, both control surfaces could perform rotation oscillations about their leading edge hinge axes. Between the wing and the control surface leading edges and also at the spanwise separation line of both flaps there was a gap of about 1 mm width.

A general view of the model and the test set-up in the open test section of the 3 x 3 wind tunnel of AVA, Göttingen, is given in Figure 2. The rigid body rotation oscillations of the wing together with the two control surfaces have been excited by use of three individually driven electrodynamic shakers. Therewith all mode shapes of interest could be excited, in particular those at which alternatively the inner or the outer flap or even both were oscillating with different phases and amplitudes relative to each other and relative to the wing. In order to realise a turbulent boundary layer on the model a tripping wire was arranged on the upper and the lower side of the wing along and near the leading edge, as is also seen from Figure 2. Finally, it is mentioned that the model was braced in the rotation axis in horizontal direction by steel wires, in order to maintain a pure rotation mode of the wing, see Figure 2.

3. DISCUSSION OF THE TEST RESULT

3.1 General Remarks

The investigations have been performed at model vibration frequencies up to 10 Hz, for which the model could be considered as sufficiently rigid as it was verified by special measurements. Thus, a maximum reduced frequency

$$\omega^* = \frac{\omega l}{2V} \approx 1.2 \qquad (1)$$

could be realized.

In the following, for the presentation of the complex unsteady pressure amplitudes, a non-dimensional unsteady pressure coefficient

$$\Delta c_p = \frac{p_{lower} - p_{upper}}{q} = \Delta c_p' + i\Delta c_p'' \qquad (2)$$

is used, where p_{lower} is the pressure amplitude at the lower side of the wing, p_{upper} the pressure amplitude at the corresponding opposite upper side of the wing and q the dynamic pressure of the undisturbed flow. Furthermore, for the sake of completeness, in all graphs the mode shapes together with the angular vibration amplitudes of the wing, A_w, of the inner flap, $A_{i.f.}$, and the outer flap, $A_{o.f.}$, are indicated. Thereby it is mentioned that, due to the position of the rotation axis of the swept wing normal to the flow direction, streamwise profile sections of the wing were undergoing both translation and pitching oscillations, what turns out to be of importance in the following discussions. Finally, it is mentioned that the pressure values in the graphs discussed in the following are not normalized with respect to a special reference amplitude.

3.2 Control Surface Oscillations

We next turn to the discussion of the test results obtained for those mode shapes at which only the control surfaces were oscillating, the wing being in an undeflected stationary position. Starting with a mode shape where both flaps are exactly vibrating in-phase and with exactly the same amplitude of rotation (that is to say, where both flaps are connected to one single flap), it is seen from Figure 3 that the wellknown real part pressure singularities are nearly the same for all three sections, because the flow in this region along the span behaves almost two-dimensional. This is also indicated in Figure 4, where the measured spanwise pressure loading along the sections IV and V is illustrated. The small irregularities near the leading edges and the common side edge are stemming from second order flow phenomena at the open gap.

The measured chordwise pressure amplitudes for a mode shape at which only the inner flap is oscillating, the outer flap being fixed as an integral part of the wing, is illustrated in Figure 5. Again the pressure peaks at the leading edge of the oscillating inner flap are striking. However, towards the forward outer side corner of the flap, the measured pressure peaks become smaller and finally disappear along the wing span. In span direction at the outer side edge of the oscillating flap, see Figure 6, the theoretically expected change of the shape of the pressure curves appears. However a (logarithmic) singularity of this slope curve with a tangent normal to the wing surface, as predicted by Landahl, has not been measured, what may probably be explained by the pressure equalization occurring at the open side gap. Along the wing span (outer fixed flap) the pressure amplitudes drop gradually to zero.

Similar effects have also been found for the corresponding mode shape, at which only the outer flap was oscillating, the inner flap being fixed to the wing. This is to be seen from Figure 7 and Figure 8.

Rather informative results have been found for that mode shape, at which both flaps were vibrating relative to each other with a phase shift of 180 degrees and with almost the same amplitude of rotation. The measured pressure distributions in chord direction are illustrated in Figure 9. Due to the phase difference a change in sign of the pressure amplitudes on the flaps in both the real and the imaginary parts appears. Again, in the measuring sections I and III, the wellknown leading edge pressure singularities are emerging. These pressure peaks become smaller towards the common side edge of the flaps and, finally, nearly disappear there at the forward leading edge corners because of almost the same rotation amplitudes, as is obviously to be seen from Figure 9. Remarkable, however, remains the fact that the pressure amplitudes near the wing leading edge have the same (positive) sign along the whole wing span.

The corresponding pressure distribution measured on both flaps in span direction is illustrated in Figure 10. Along the common side edge the unsteady pressure becomes nearly zero. There the pressure gradient in fact has a maximum, but a singularity of the pressure slope curve, as predicted by Landahl, is not indicated what probably may be explained by the influence of the open side gap as already mentioned. Moreover, the real part Δc_p in section V shows a somewhat curious behavior.

3.3 Combined Wing and Control Surface Oscillations

We, now, turn to the discussion of the test results obtained for combined wing and control surface vibration modes. First we consider a mode shape at which the wing is performing a rotation oscillation about a rotation axis as indicated in Figure 1, and both flaps are oscillating in phase with the wing and with exactly the same amplitude of rotation, that is to say, as one full span flap. The relating test results are illustrated in Figure 11 and Figure 12. As it may be expected from theory in each chordwise section two pressure singularities are now appearing, one at the leading edge of the wing and the other at the leading edge of the flaps. The theoretically square-root pressure singularity at the wing leading edge is rather distinctive, although the wing amplitude is much smaller. This stems from the fact that the effects of the wing and the flap rotation are added up as a consequence of the same phase. Again, in the region between the measuring sections I and III, the flow is nearly two-dimensional, as is also to be seen from the spanwise pressure distribution illustrated in Figure 12.

The test results for the corresponding mode shape at which the wing and the flaps are vibrating in anti-phase are given in Figure 13 and Figure 14. In contrary to the preceding example now the flap leading edge pressure singularity is much more emerging, whereas the wing leading edge pressure singularity is almost vanishing. For that there are two reasons, namely the relatively small wing rotation amplitude and the opposite phase of vibration.

Finally, the measured pressure distributions of a mode shape, at which the wing and the outer flap are oscillating in-phase, and the inner flap is oscillating in anti-phase, are illustrated in Figure 15 and Figure 16. The real part $\Delta c'_p$ in chord direction exhibits in all three measuring sections the (quadratic) pressure singularity at the wing leading edge and the wellknown (logarithmic) pressure singularities at the flap leading edges. As for the latter, a comparison of Figure 15 with Figure 9, however, reveals rather remarkable differences. Although the outer flap is oscillating in anti-phase with respect to the inner flap, there is no change in sign of the flap leading edge peak values as it might be expected from Figure 9. Moreover the pressure peak values of the outer flap are much smaller than those of the inner one, although the rotation amplitudes of both flaps are the same. The reason for this illustrative behavior is the interfering effect of the oscillating wing, whose streamwise sections at the outer region are undergoing considerable heaving motions, too. In span direction the already wellknown behavior at the common side edge of the flaps was found, as it may be seen from Figure 16.

4. CONCLUSIONS

Summarizing it may be said that the above discussed test results revealed an interesting insight into the very complicated physical relations of the unsteady pressure development on a harmonically oscillating multi-control lifting surface system. The intensity of the measured pressure peaks at the control surface leading edges is highly influenced by the oscillating wing and also by the phase between the oscillating wing and flap. Furthermore three-dimensional effects are of importance. The pressure gradients in span direction at the control surface side edge were showing essentially the behavior predicted by Landahl. Thus it may be concluded that Landahl's wellknown pressure loading series, see Ref.5, for the solution of the oscillating lifting surface problem in subsonic flow, based on the kernel-function approach and a relating collocation procedure, are well expressing the physical relations of the unsteady pressure behavior along the control surface edges. It would be desirable to explain the applicability of these pressure loading functions by comparing calculations.

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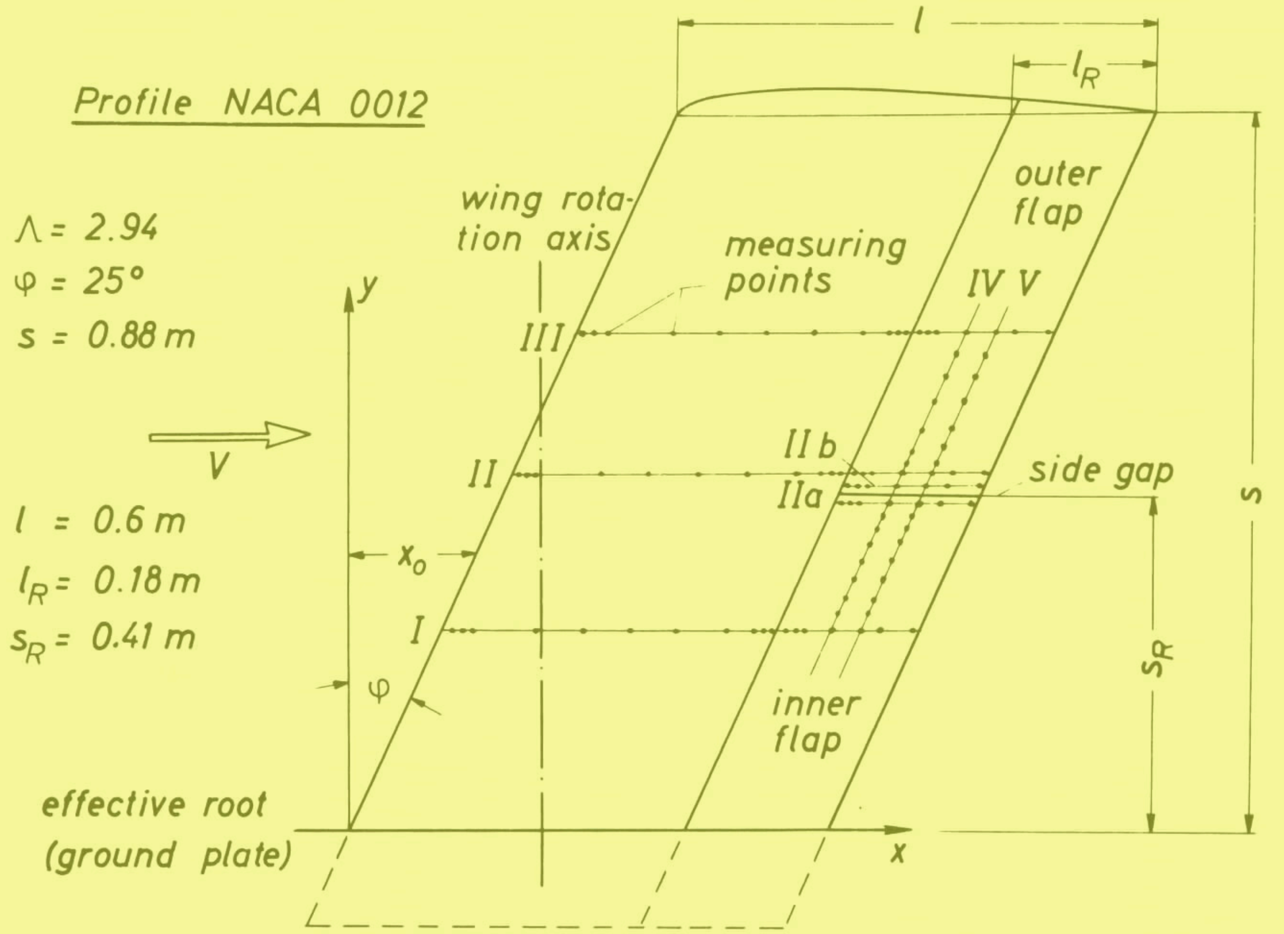

Fig.1 Schematic illustration of the test model and the location of the pressure measuring points

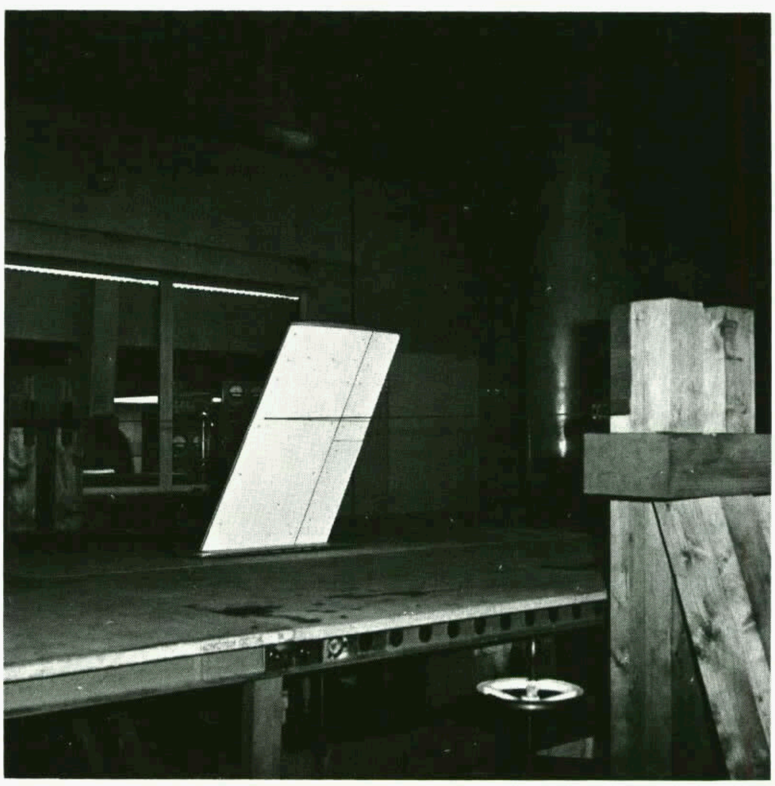

Fig.2 Model in the open test section of the 3 x 3 m wind tunnel

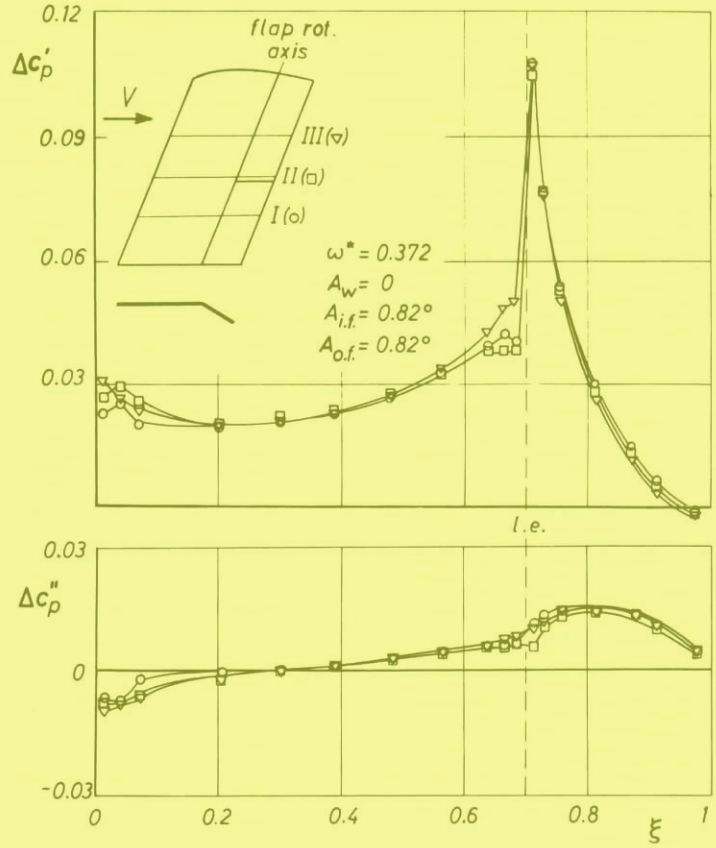

Fig.3 Pressure distribution in chord direction for a mode shape at which both flaps are oscillating with the same phase and amplitude, the wing being in an undeflected stationary position

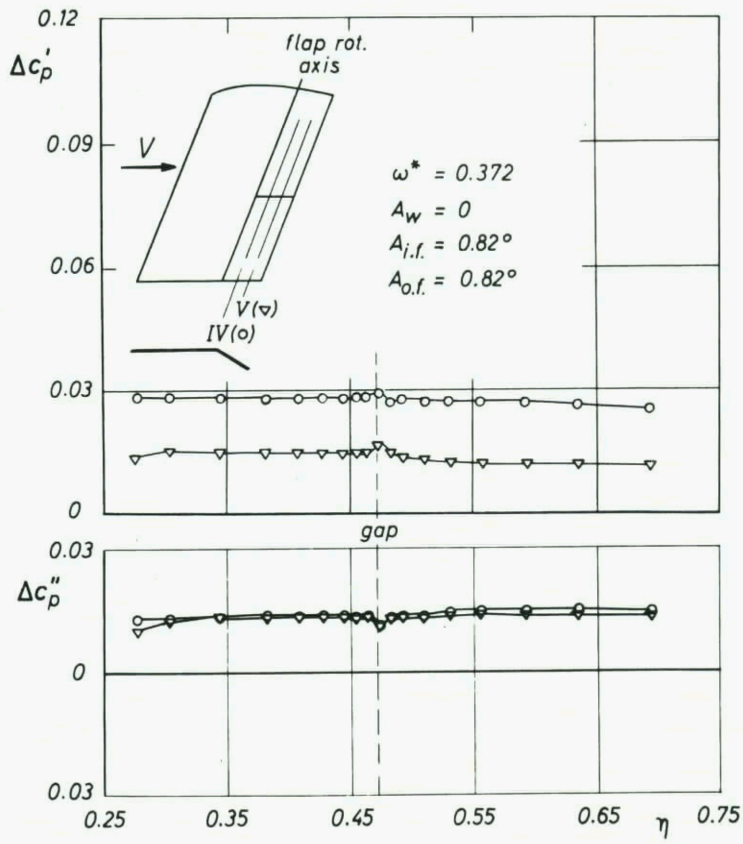

Fig.4 Pressure distribution in span direction for a mode shape at which both flaps are oscillating with the same phase and amplitude, the wing being in an undeflected stationary position

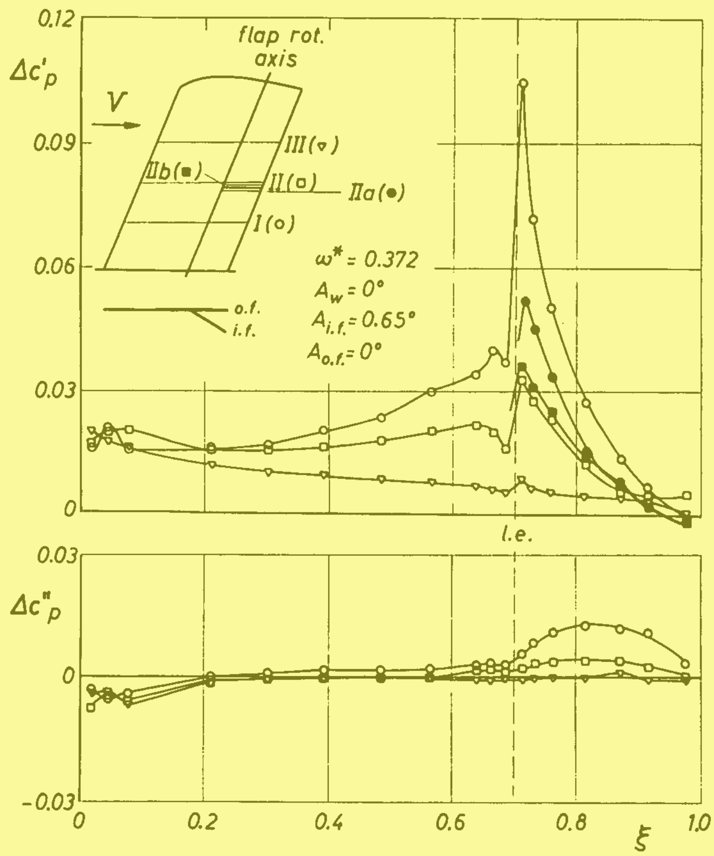

Fig.5 Pressure distribution in chord direction for a mode shape at which only the inner flap is oscillating, the outer flap and the wing being in an undeflected stationary position

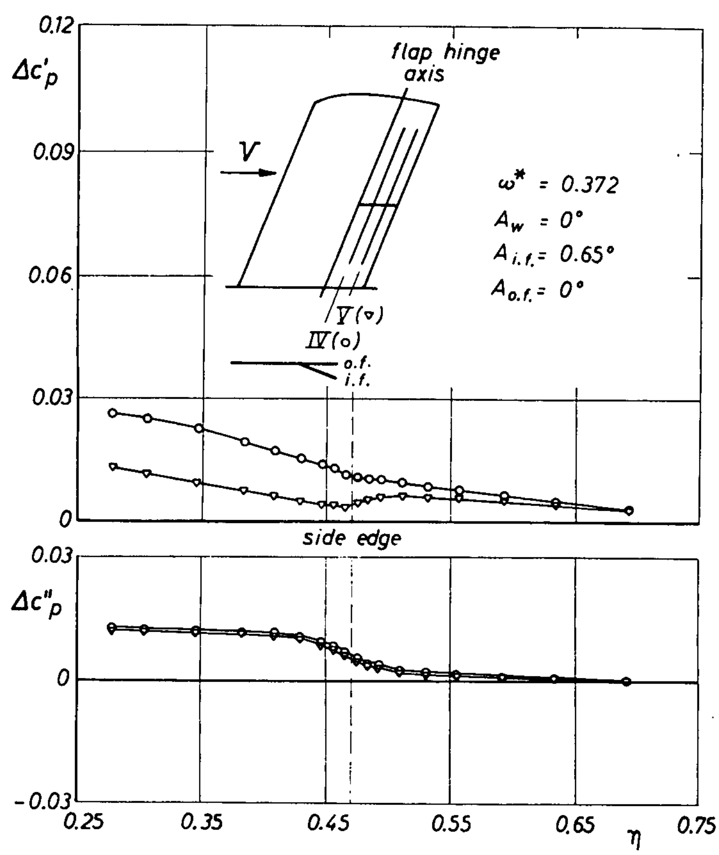

Fig.6 Pressure distribution in span direction for a mode shape at which only the inner flap is oscillating, the outer flap and the wing being in an undeflected stationary position

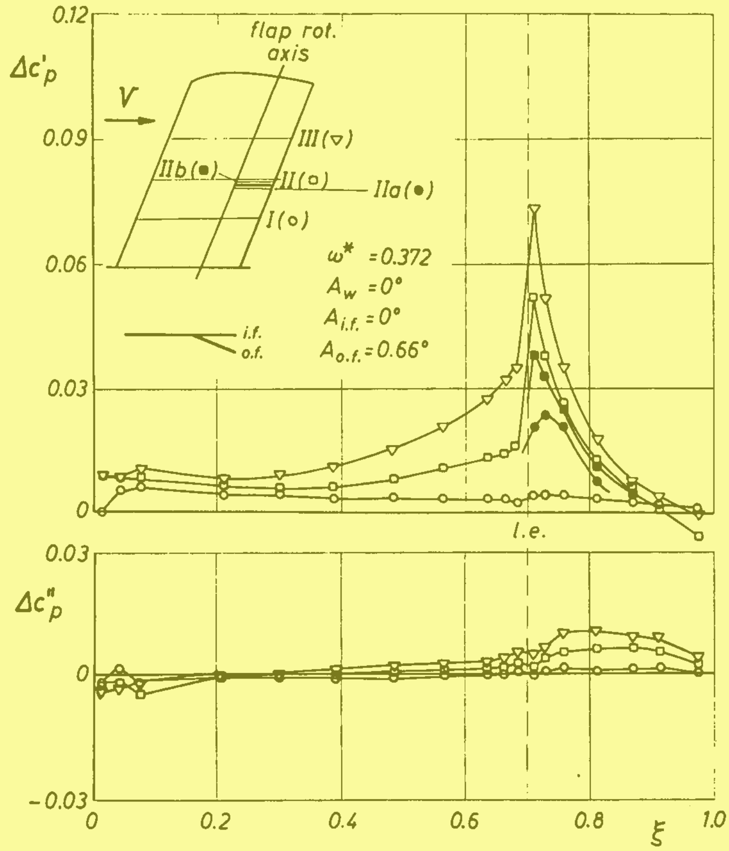

Fig.7 Pressure distribution in chord direction for a mode shape at which only the outer flap is oscillating, the inner flap and the wing being in an undeflected stationary position

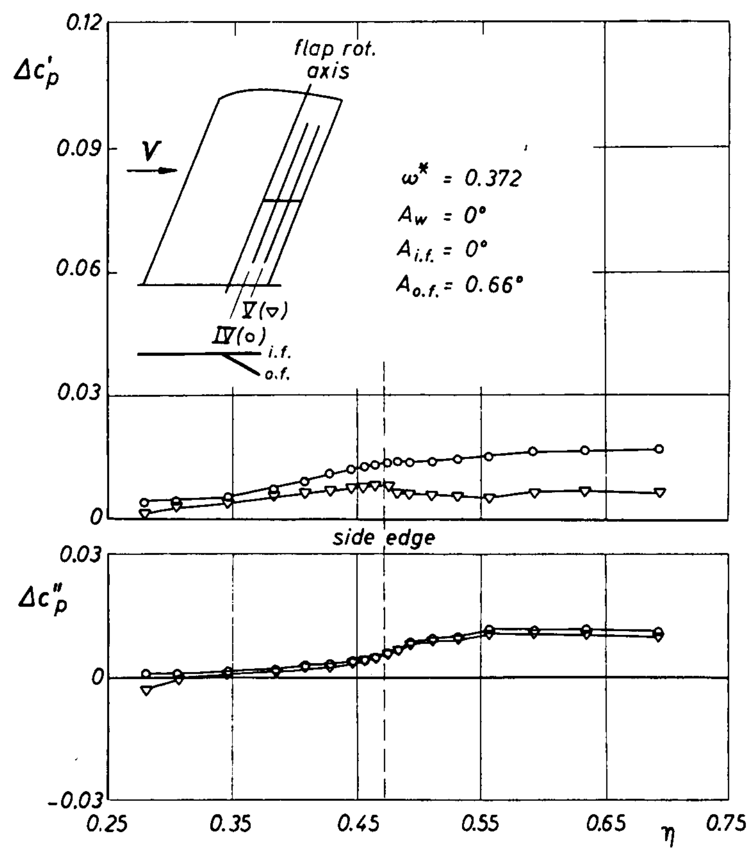

Fig.8 Pressure distribution in span direction for a mode shape at which only the outer flap is oscillating, the inner flap and the wing being in an undeflected stationary position

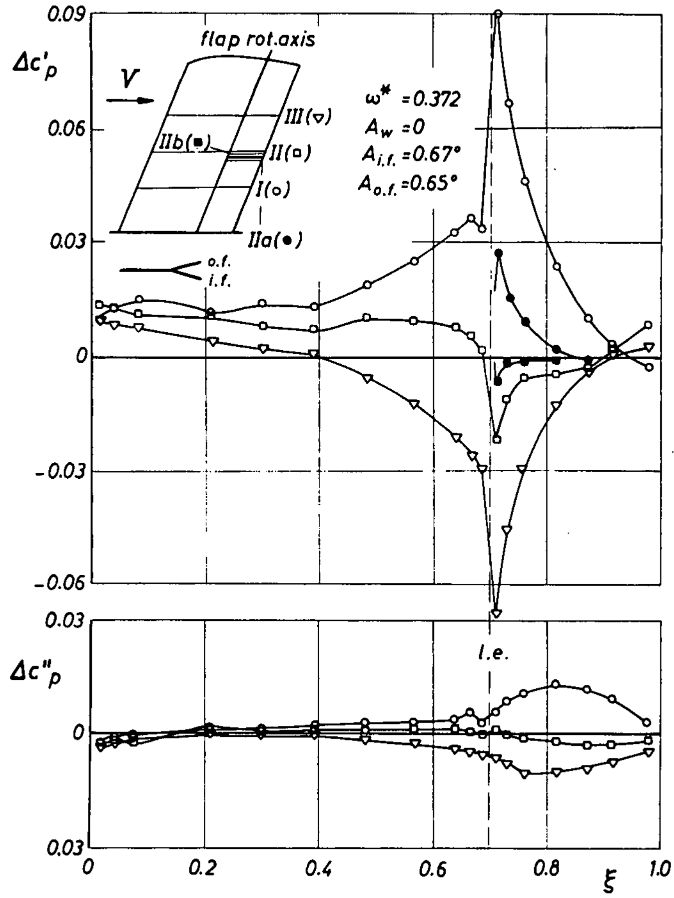

Fig.9 Pressure distribution in chord direction for a mode shape at which both flaps are oscillating in anti-phase, the wing being in an undeflected stationary position

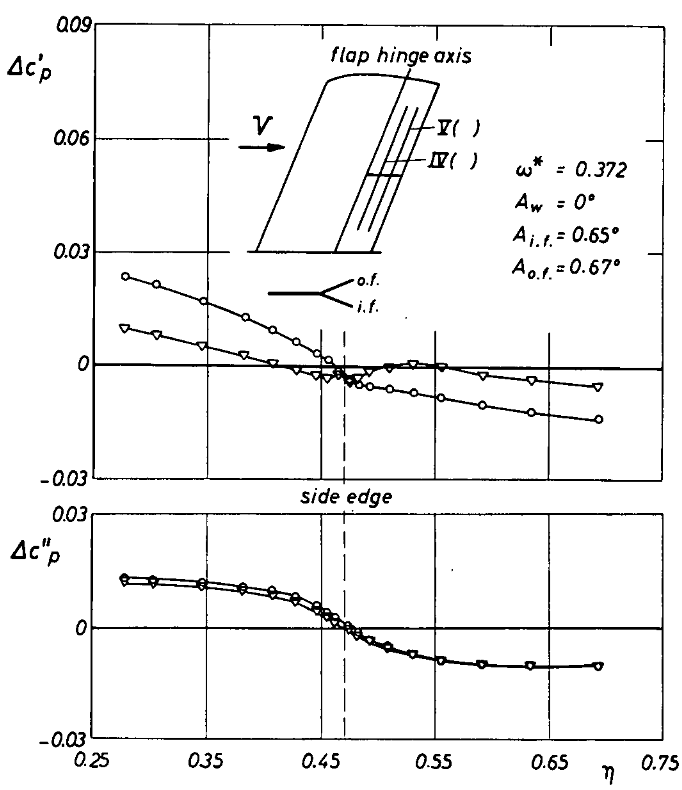

Fig.10 Pressure distribution in span direction for a mode shape at which both flaps are oscillating in anti-phase, the wing being in an undeflected stationary position

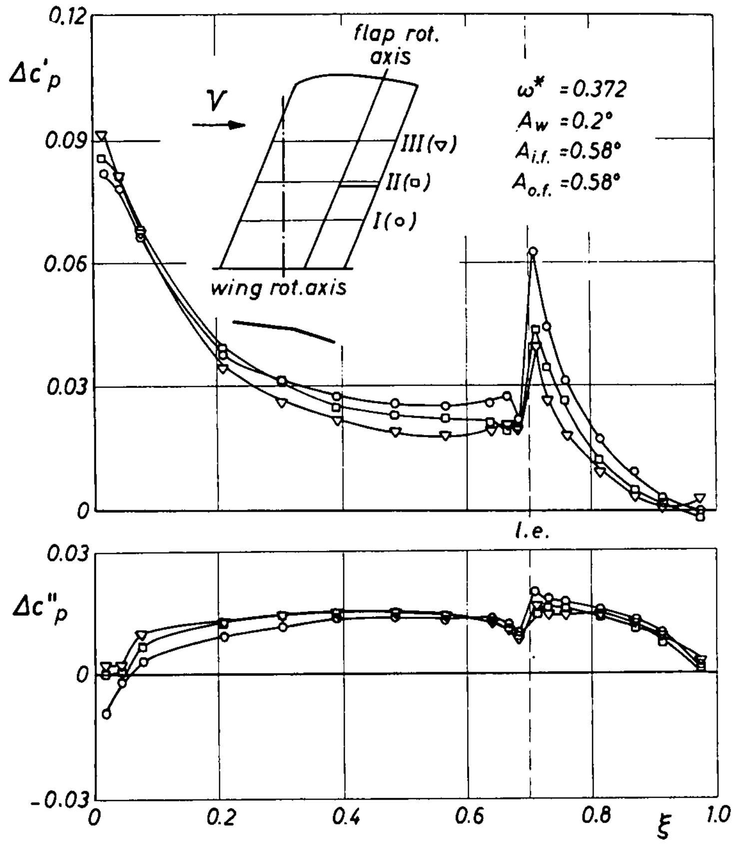

Fig.11 Pressure distribution in chord direction for a mode shape at which the wing is performing a rotation oscillation and both flaps are oscillating in-phase to the wing and with exactly the same amplitude

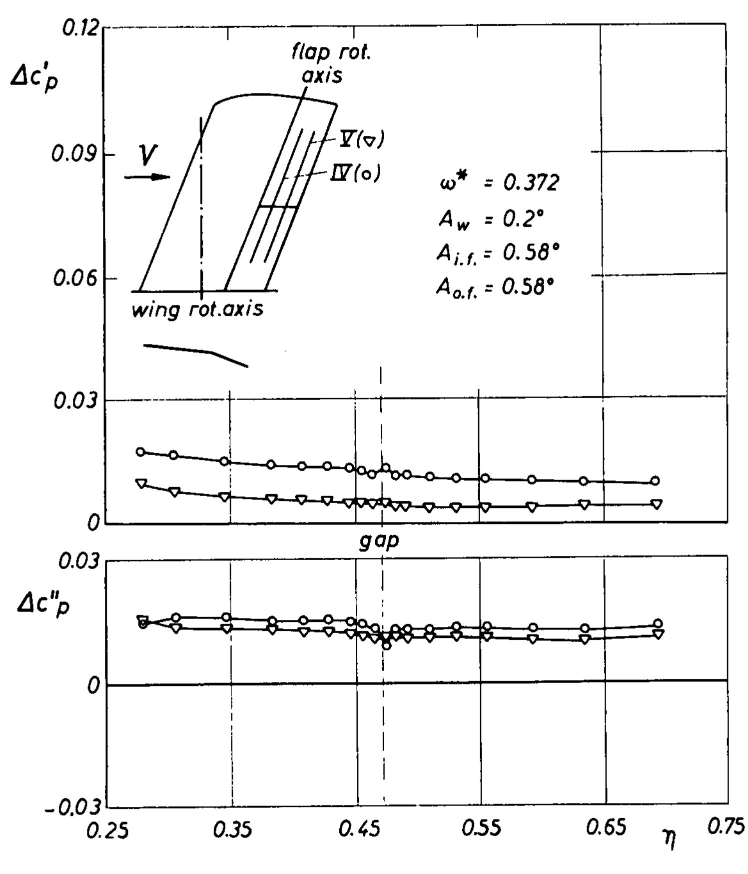

Fig.12 Pressure distribution in span direction for a mode shape at which the wing is performing a rotation oscillation and both flaps are oscillating in-phase to the wing and with exactly the same amplitude

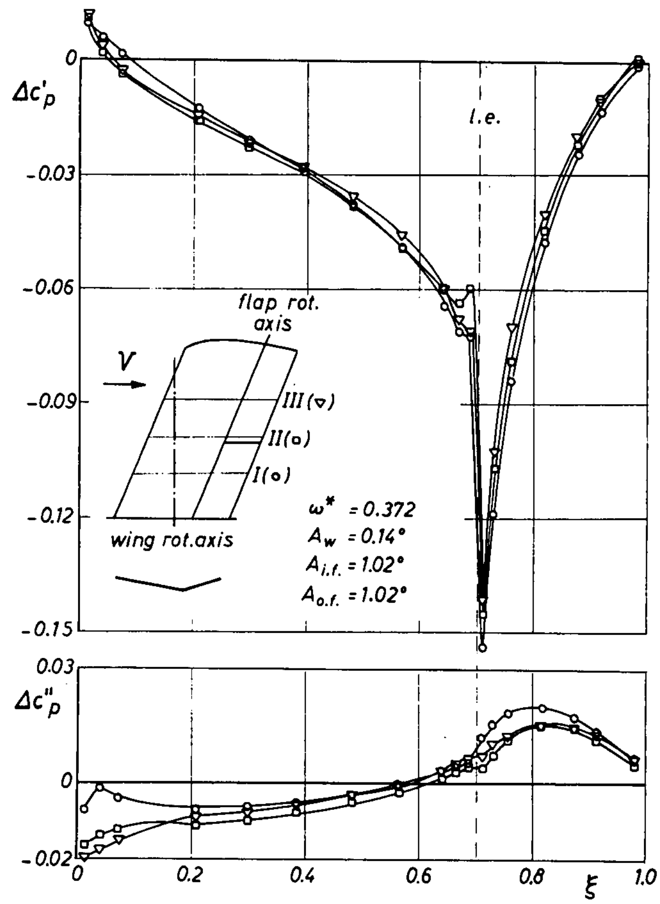

Fig.13 Pressure distribution in chord direction for a mode shape at which the wing is performing a rotation oscillation and both flaps are oscillating in anti-phase to the wing and with exactly the same amplitude

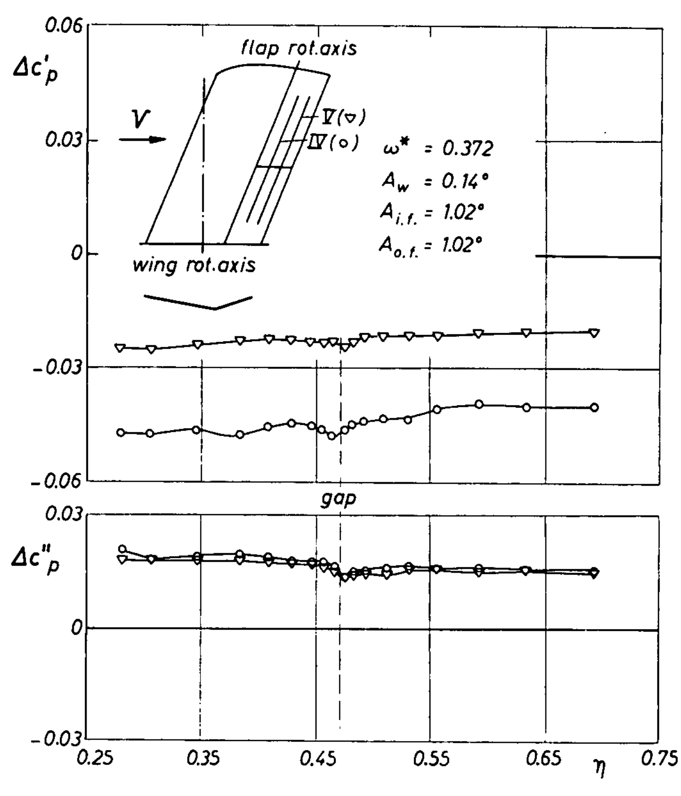

Fig.14 Pressure distribution in span direction for a mode shape at which the wing is performing a rotation oscillation and both flaps are oscillating in anti-phase to the wing and with exactly the same amplitude

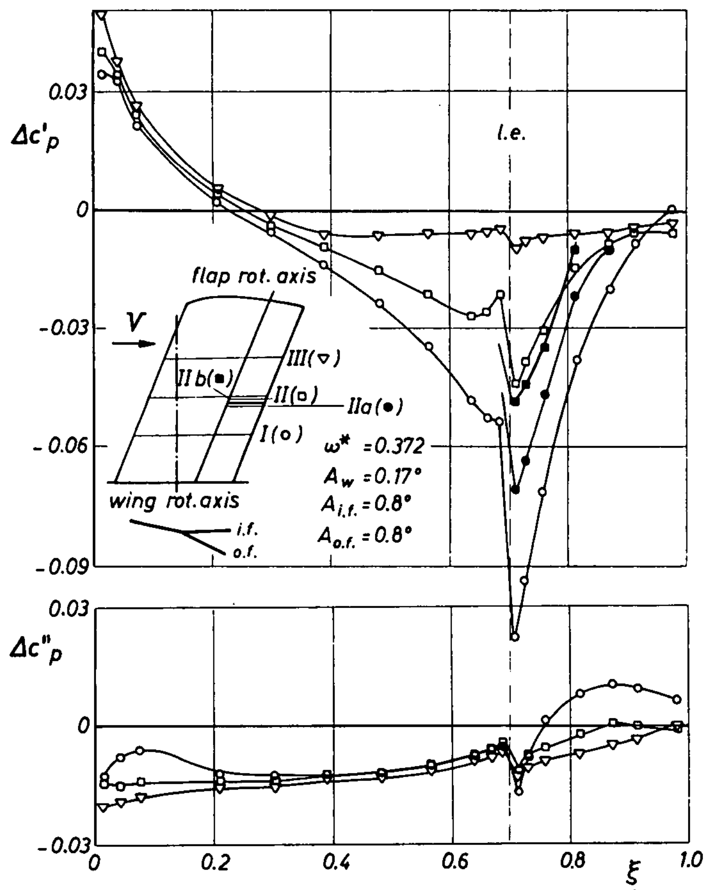

Fig.15 Pressure distribution for a mode shape in chord direction at which the wing and the outer flap are oscillating in-phase and the inner flap is oscillating in anti-phase

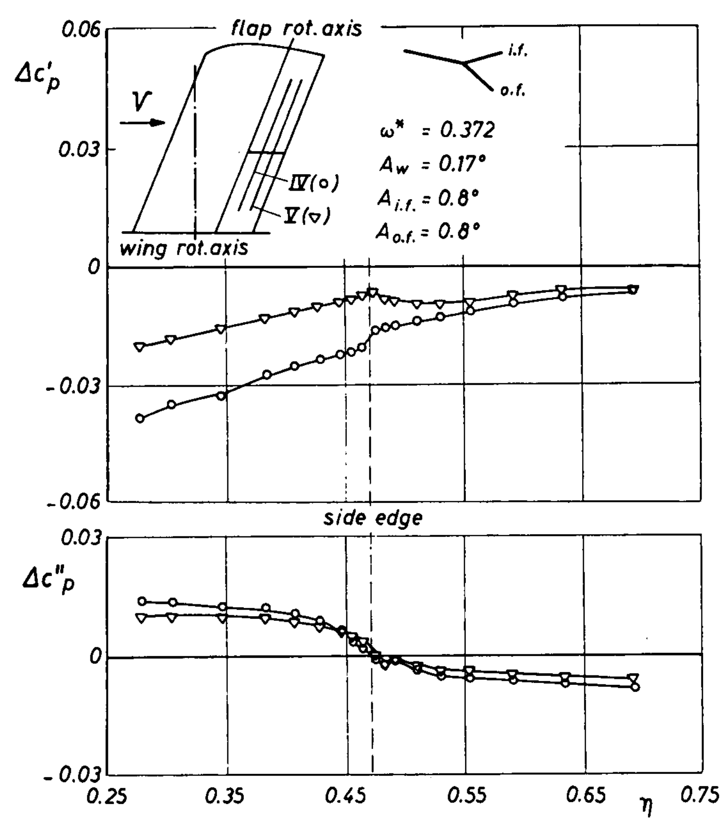

Fig.16 Pressure distribution for a mode shape in span direction at which the wing and the outer flap are oscillating in-phase and the inner flap is oscillating in anti-phase

and limitations of various methods, to discuss applications and means of evaluating the methods numerically and to suggest future developments. Part I contains the four papers of general scope selected as contributions to the AGARD Manual on Aeroelasticity; the remaining eleven papers are in Part II.

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