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AN EXPERIMENTAL STUDY OF THE DYNAMIC FORCES ACTING ON FIXED AND VIBRATING TWO-DIMENSIONAL AEROFOILS

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AN EXPERIMENTAL STUDY OF THE DYNAMIC FORCES ACTING ON FIXED AND VIBRATING TWO-DIMENSIONAL AEROFOILS

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ABSTRACT

An experimental study has been conducted to try to understand and classify the aerodynamic instabilities and random excitations occurring on two-dimensional aerofoils at non-zero incidence angles and subsonic flow speeds. Particular attention has been paid to stall flutter. In order to investigate separately the buffeting phenomenon and the risk of aeroelastic instability at high incidence, the random pressure field was measured on the clamped aerofoils, whilst the vibrating aerofoils yielded unsteady aerodynamic coefficients which reveal the possibility of instabilities on certain torsion modes. The maximum vibration reduced frequency was 0.45. The Mach number range was 0.3–0.95–Maximum incidence 14°. Shadowgraph flow visualizations were filmed at high speeds (1000 and 3000 frames/sec). Results show the flow conditions for random excitation (buffeting) and for two types of aerodynamic instabilities. One of these is stall flutter, while the other is a shock instability on the lower surface of the aerofoil.

1 – INTRODUCTION

Though the problem of aerofoil vibration at high angles of incidence has been the subject of numerous studies [1], it is frequently not quite clear whether these vibrations are due to an external excitation force resulting from turbulence, or else to the presence of an aeroelastic instability [2]. The purpose of the study reported in this paper is to attempt to classify the problem by determining the types of aeroelastic instabilities and excitations that can exist on a two-dimensional aerofoil in subsonic flow. The well known two-degree-of-freedom bending-torsion flutter is excluded from this discussion.

Fluctuating aerodynamic forces can be classified into two distinct groups : those that are independent of the flow boundary conditions, which in the present case is the vibration of the aerofoil, and those that only exist by virtue of the vibrations they engender. Of course, these two types of forces can coexist.

– Fluctuating aerodynamic forces independent of aerofoil vibration are generated by turbulence or other external source and represent external excitational forces. In practice these usually appear as broad-band random forces. The structural response to this excitation can be readily calculated once the input force spectrum and the structural admittance are known.

The particular and well known case of vortex shedding by blunt bodies produces a very periodic aerodynamic lift [3]. However this lift force is modified by vibrations of the body at or near the shedding frequency and thus this vortex shedding does not act as a simple excitational force.

- Fluctuating aerodynamic forces engendered by aerofoil vibrations can have different forms :

a) if the flow field can be likened to a one-degree-of-freedom vibratory system (e.g. vortex shedding without any oscillatory motion) the flow and vibration will couple at (or near) the coincident frequency and can cause self-excited oscillations.

b) when the flow field is not itself an independent vibratory system, its oscillatory characteristics are entirely induced by the motion. The resulting unsteady forces will have either a damping or an excitational effect according to the phase angle between the vibratory movement and the force. The excitational case is equivalent to a negative damping and is a single-degree-of-freedom flutter. A good example of this is the galloping of telephone cables.

2 - EXPERIMENTAL METHODS

The tests were carried out in the S3-MA ONERA wind tunnel (blow-down tunnel with a 0.78 m x 0.56 m working section) on a two-dimensional symmetrical NACA 63A015 aerofoil section. The tunnel walls parallel to the model were permeable (figure 1).

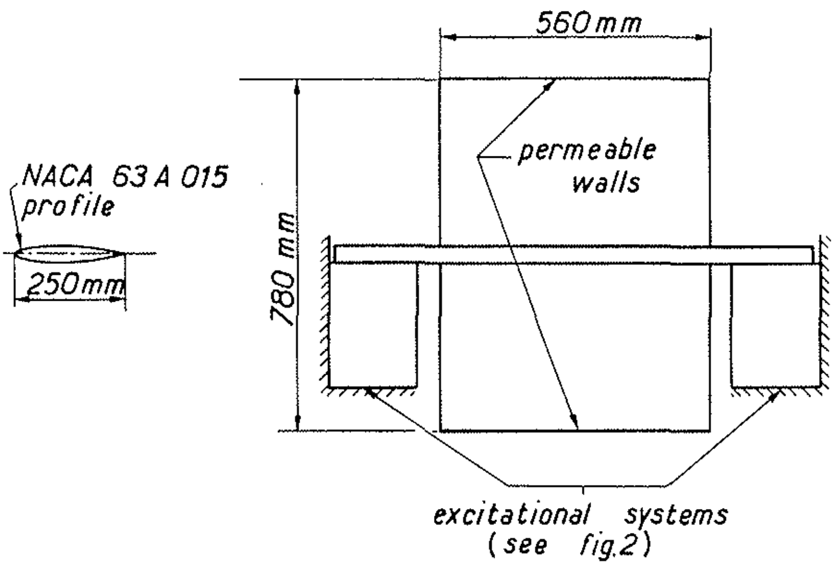

Fig. 1 — Wind tunnel and model.

The model was rigid and mounted on torsional springs allowing for an overall pitching motion at frequencies between 30 and 60 Hz and amplitudes of up to 0.5 degrees r.m.s. The vibratory motion was controlled by four electrodynamic shakers.

The experimental set-up (figure 2) was devised in such a way as to allow for shadowgraph flow visualizations on the aerofoil upper surface. The images were recorded with a 16 mm camera at a rateof 1000 or 3000 pictures per second.

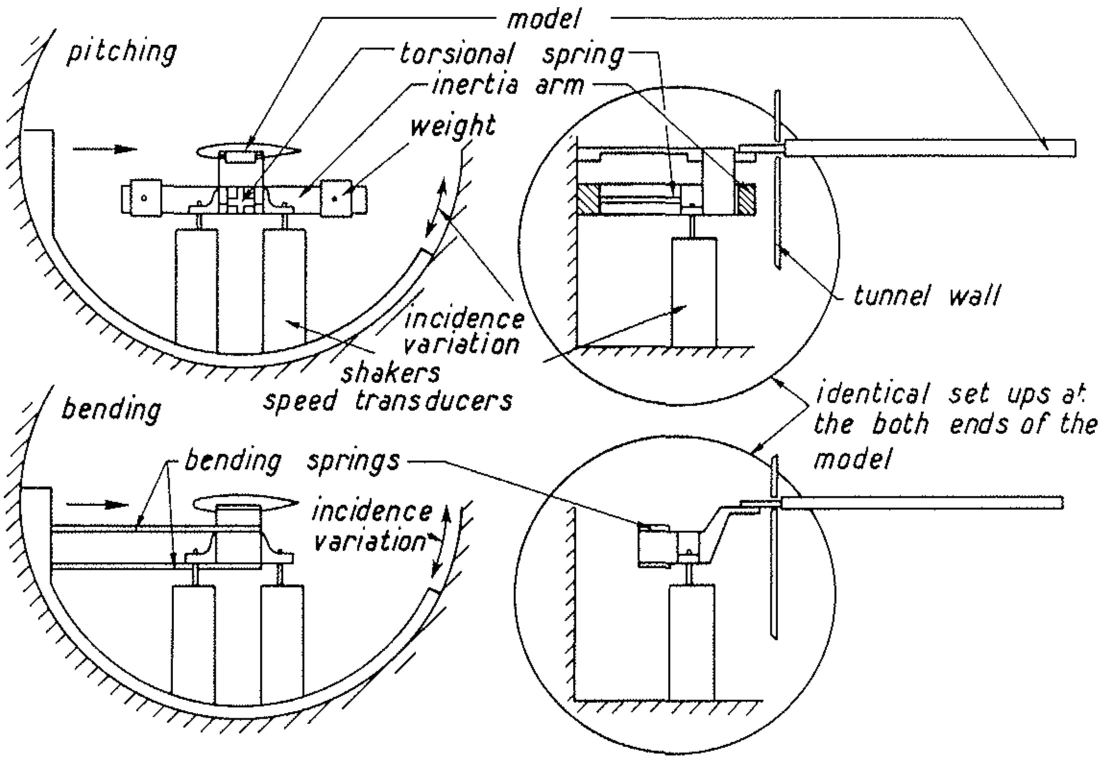

Fig. 2 — Test set-up.

The fluctuating lift and moment were measured by means of pressure transducers placed at regular chordwise intervals in the same cross-sectional plane. The transducers used were of the semi-conductor gauge type (Kulite CQL-080-5) with natural membrane frequencies greater than 70 kHz. The lift and moment were obtained by a real time summation of the respective components of the pressure measured by each transducer. This method for measuring fluctuating aerodynamic forces has a number of advantages over the more standard strain-gauge balance and in particular in that : (i) no errors are caused by end effects due to the tunnel walls, (ii) fluctuating pressure distributions are obtained, (iii) there is no need for inertial force correction (for the case of the vibrating model)

(iv) the measurements are unaffected by any mechanical non-linearities inherent in the vibrating test set-up. This method is illustrated schematically in figure 3.

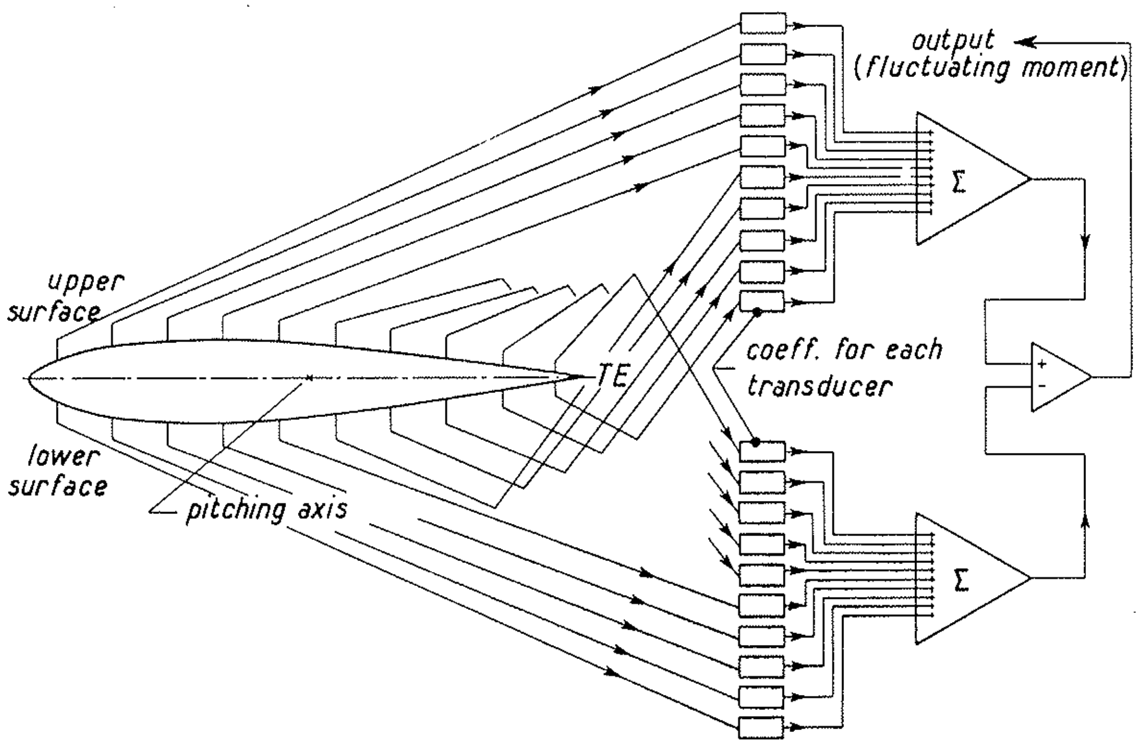

Fig. 3 – Unsteady moment measurement.

Tests were carried out with a view to determining all the instabilities and fluctuating forces existing on this aerofoil at subsonic upstream flow speeds. The angle of incidence was varied from 0° to 14°, the upstream flow-speed from Mach 0.3 to Mach 0.95 and the frequency of vibration from 30 to 60 Hz. The pitching axis was at 37.5 % of the chord.

3 - EXPERIMENTAL RESULTS

The experimental results are presented under two distinct headings : those obtained on the clamped aerofoil model and those given be the vibrating aerofoil. This division facilitates the distinction between unsteady lift and moment forces that are independent of aerofoil motion and those that are induced by this motion.

3-1 - Clamped aerofoil section

- The fluctuating lift and moment are function of the angle of incidence and of the flow speed. In figure 4 the overall r.m.s. fluctuating lift is plotted against these two parameters for a wide frequency band (2 Hz to 2 kHz). At each angle of incidence there is a definite flow speed at which the level of the fluctuating forces changes radically - the greater the angle of incidence, the lower this critical flow speed.

The fluctuating forces that exist at zero incidence (figure 4) are due to boundary layer and wind tunnel noise effects which are not necessarily identical and in phase on the upper and lower surfaces and hence do not cancel out.

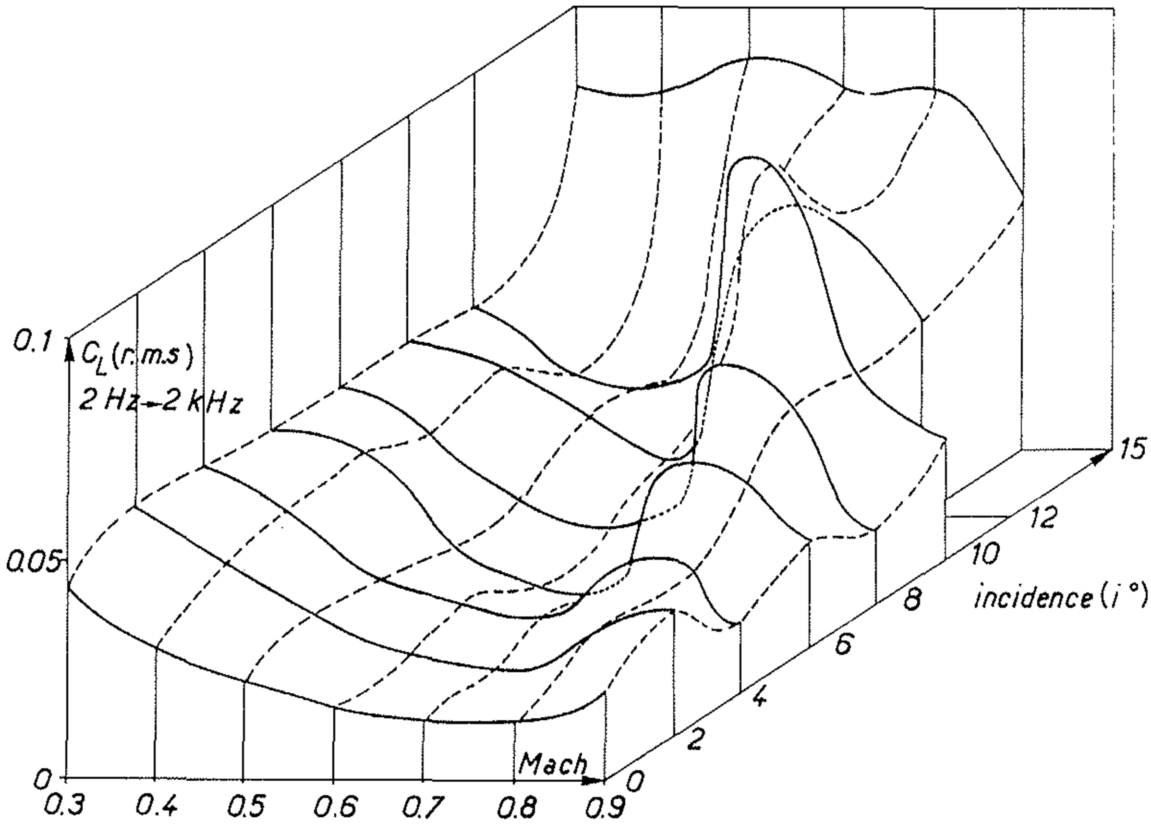

Fig. 4 — Fluctuating lift plotted against Mach number and angle of incidence.

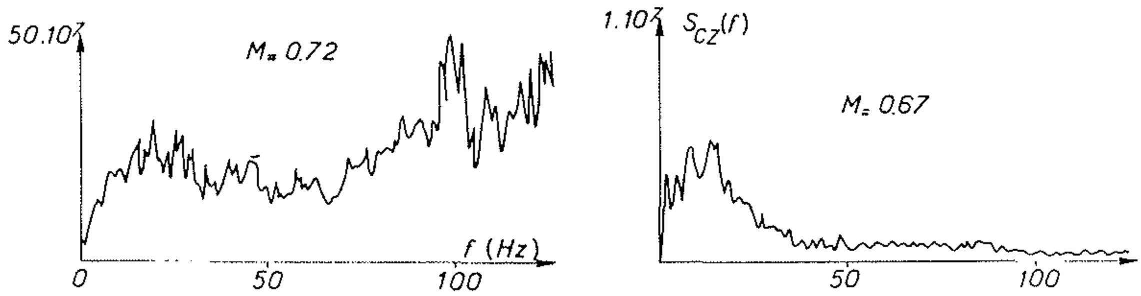

Fig. 5 — Frequency spectra at speeds below and above the separation speed - i = 8 °.

The frequency distribution of the increase in fluctuating forces at the critical speed is shown on figure 5. The two spectra are for an angle of incidence of 8° and flow speeds of Mach 0.67 and 0.72 respectively. These two values are on either side of the critical speed. The rise in spectral density level is of almost an order of magnitude and greater at higher (> 40 Hz) than at lower frequencies.

These results give reason to suppose that there is flow separation at the critical speeds since the turbulence behind a separating point produces large fluctuating forces. This hypothesis is confirmed by the flow visualization and by the fluctuating pressure distributions, as described below.

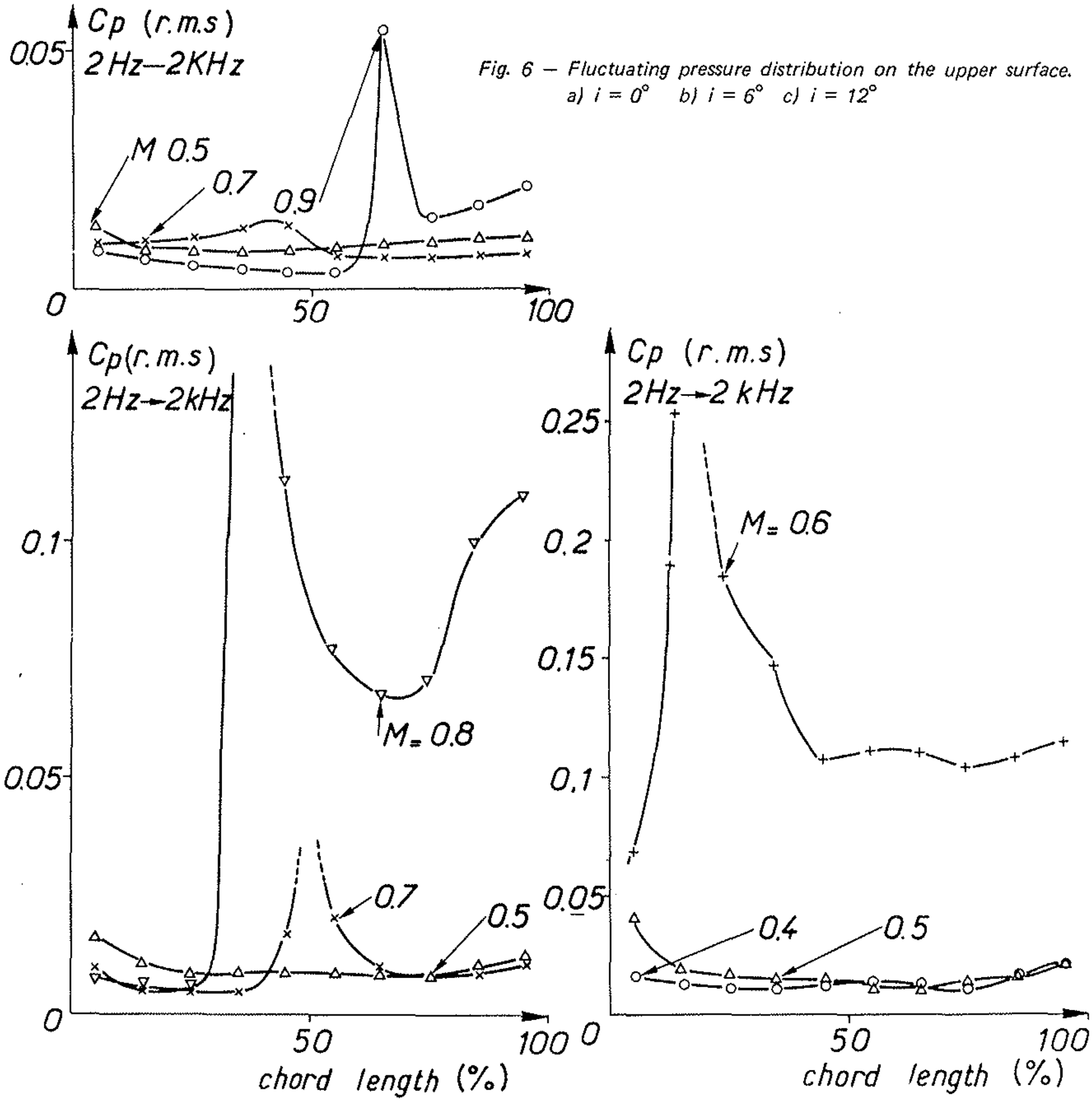

Fig. 6 — Fluctuating pressure distribution on the upper surface.
a) i = 0° b) i = 6° c) i = 12°

- <u>The distribution of fluctuating pressures</u>. Figures 6 show typical pressure distributions (upper-surface only) at angles of incidence of 0°, 6° and 12° respectively. Pressure levels where $Cp < 0.03$ (Cp = pressure level r.m.s./$(1/2 \rho V^2)$) show unseparated regions, while behind flow separation points this level is considerably higher. The peaks that can be seen on many of the curves are due to shock waves which are never perfectly steady and can oscillate considerably, thus causing large local pressure fluctuations. The shock movement is over a large frequency band and random in character. In the examples shown, separation always takes place behind the shock, though of course the presence of a shock is not a prerequisite for flow separation. Similarly a shock can exist without separation behind it, as in figure 6b for Mach 0.7.

- <u>Limits for large fluctuating forces</u>. According to the above discussion the limits of incidence and flow speed at the appearance of large fluctuating pressures are in fact the flow separation limits. They are fairly easy to distinguish in the present case, and given in figure 7 where the critical speed is plotted against the angle of incidence.

These results obtained on the clamped model lead to the conclusion that the external flow excitation of a two-dimensional aerofoil only exists in the presence of flow separation. This is the phenomenon which is often described as buffeting.

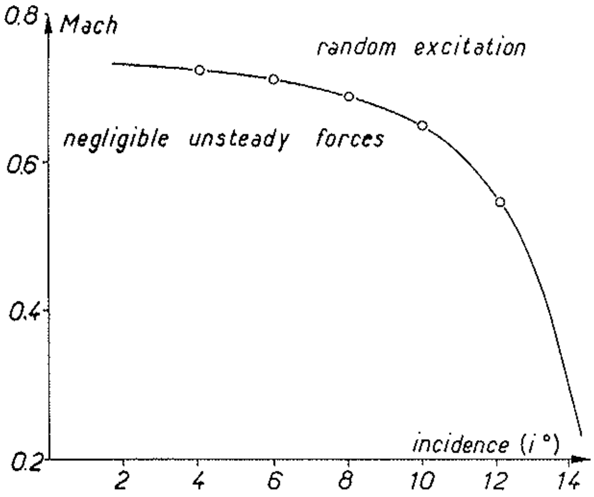

Fig. 7 — Limits of large random pressure fluctuations.

3-2 <u>Vibrating aerofoil</u>

In any event the vibrational motion produces surface pressures at the frequency of vibration. These induced forces can be either excitational (instability) or damping, depending on their phase relation with the movement.

Under conditions where flow separation produces large unsteady pressures, the vibratory motion in no way modifies the broad-band random forces. The periodic forces at the frequency of vibration merely add to the existing spectrum. Figure 8 illustrates this with spectra measured on fixed and vibrating aerofoils under the same flow separated conditions.

Tests results on the clamped aerofoil showed that there were no flow periodicities that would be able to couple with a vibratory motion. This is confirmed by tests on the vibrating model where no instabilities of this type were encountered. However two forms of instability were found where the aerodynamic forces were induced by the motion. These were stall flutters and an instability due to the synchronized movement of a shock wave on the lower surface.

- <u>Stall flutter</u>. At angles of incidence greater than 6°, torsional instabilities were found over certain flow speed ranges. Figure 9 shows the modulus and phase of the fluctuating aerodynamic coefficient of moment (m_θ = moment$/(\frac{1}{2} \rho V^2 \theta S \frac{c}{2})$, where θ is the vibrational amplitude, S the aerofoil surface area, c the chord length) as a function of flow speed for different angles of incidence and the same frequency of vibration of 34 Hz (reduced frequency ω_{r} = 0,082 for Mach 1).

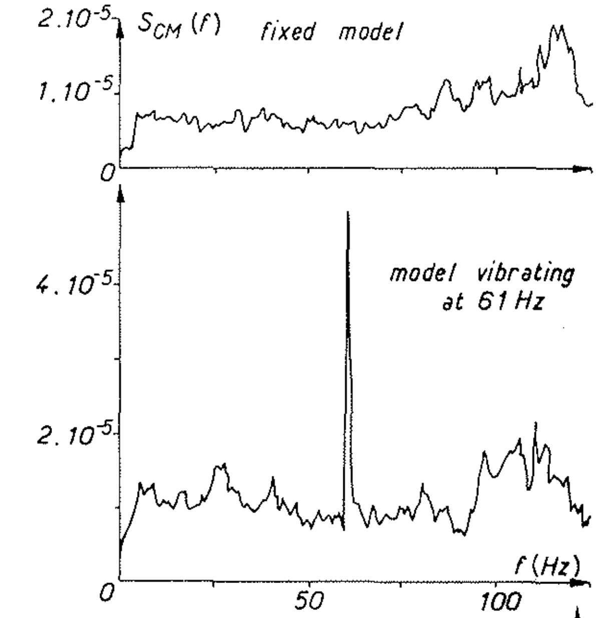

Fig. 8 — Typical moment spectra. Influence of vibrations on the separated flow pressure field.
$i = 8°$ - $M = 0.7$

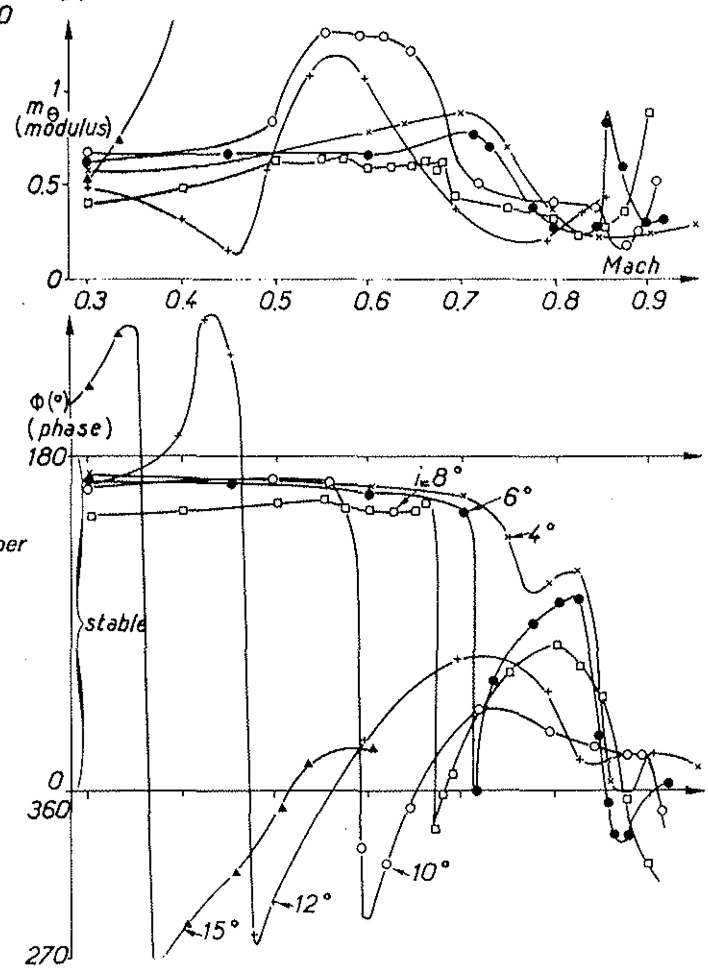

Fig. 9 — m_θ and ϕ a function of Mach number at various angles of incidence.

The phase reference chosen is such that the aerofoil is unstable when $180° < \Phi < 360°$.

On the figure one can see that the speed range for instabilities widens while the absolute stability speed limit diminish with increasing angles of incidence.

- <u>Lower surface shock instability</u>. Figure 9 also reveals at certain angles of incidence the presence of a second region of instability at flow speeds exceeding Mach 0.8. From flow visualization films, the source of the instability was found to be a shock motion on the lower surface, whose phase lag was sufficient to act as a "negative damping".

Typical lower surface pressure distributions (modulus and phase) in figure 10 show this clearly.

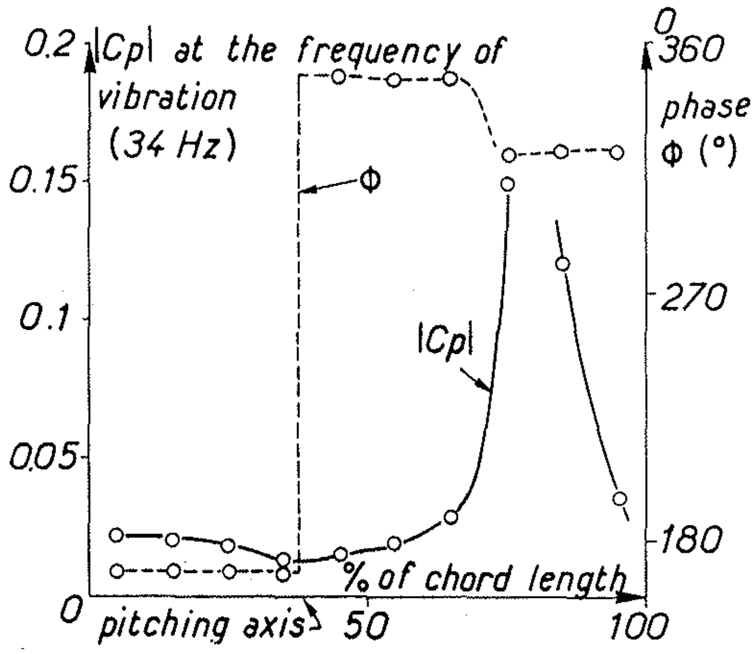

Fig. 10 — Fluctuating pressure distribution on the lower surface at $i = 8°$ and Mach 0.9.

4 - <u>CONCLUSIONS</u>

The vibrations of two-dimensional aerofoils subjected to unsteady lift or moment forces can have various causes. They may be due to stall-flutter or chock wave instabilities (auto-excitation) or else be the result of excitation by the large random pressure field in the turbulent zone of a separated flow region.

Figure 7 showed the flow speed and incidence angle limits for large random aerodynamic forces. The same type of diagram can be drawn for the limits of stall flutter. These two limiting curves are compared in figure 11 and it can be seen that they are fairly close. For the aerofoil used in the present tests, a region of instability or auto-excitation will be reached before random excitation ; however this need not be the case for other aerofoil shapes, though both limiting curves will always exist.

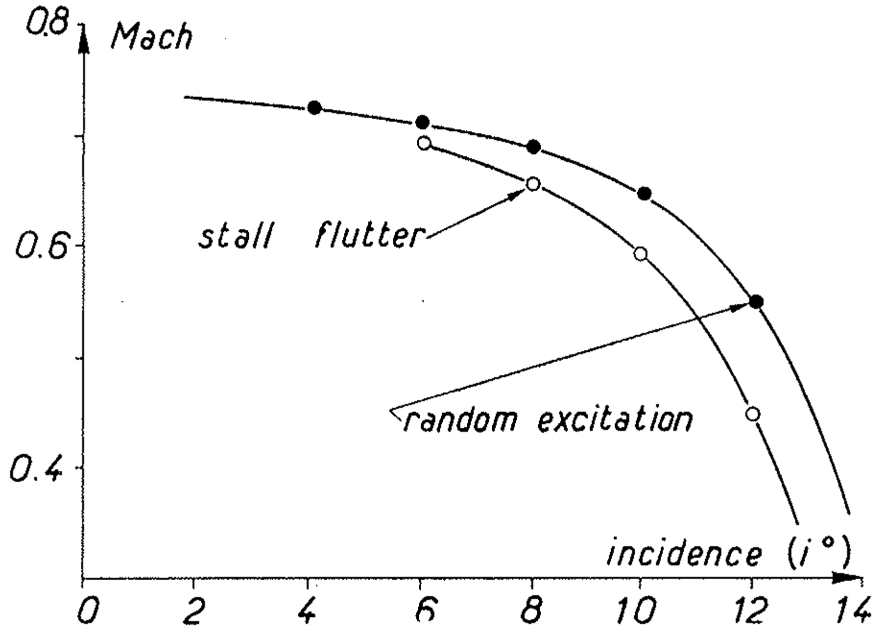

Fig. 11 – Comparison between the limiting conditions for stall flutter and for random excitation.

One may conclude that the vibrations that often limit the performance of a wing or blade are not always due to the same aerodynamic phenomenon : moreover there are cases, in particular for swept wings, where the three-dimensional flow effects may be the source of excitational forces which are non-existent in a two-dimensional test.

5 – REFERENCES

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