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Some Experiments on Control-Surface Buzz

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Some Experiments on Control-Surface Buzz*

By Yasuharu NAKAMURA** and Yoshikazu TANABE**

Summary

Experimental investigations on the control-surface buzz at transonic speeds were made with a two-dimensional airfoil-flap combination model. Experiment 1 was devoted to optical observations by using a high speed motion camera with particular emphasis on the growth of buzz, namely from the state of small amplitudes up to the limit cycle of oscillation. In Experiment 2, the measurements of the unsteady hinge moment of the flap by a free oscillation method were performed at subsonic and transonic Mach numbers.

It was found that the type of buzz occurring at the higher transonic Mach numbers shows "a soft oscillator" characteristics. Also the oscillation, at least at small amplitudes, can be associated with negative damping in potential flow and does not depend on the boundary layer effects. The measured unsteady hinge moments of the flap agreed reasonably with the values predicted by the supersonic unsteady linearized theory.

1. Introduction

The instability, commonly known as the aileron buzz, refers to a class of self-excited rotations of a control-surface on aircraft about its axis sometimes encountered during flight at transonic speeds.

Much work has already been done on this instability since 1945 when aileron vibration of a novel type was encountered in high subsonic flight[1]. Of these Lambourne's work has made an essential contribution to the understanding of the phenomenon[1),2)]. He studied the effects of the fundamental parameters on buzz—the Mach number, the airfoil section and the incidence, and has pointed out that more than one variety of buzz can occur under several transonic conditions of flow.

In the transonic region, however, the shock waves appear on the airfoil surfaces, and interact with the boundary layer, generally producing the severely separated flow around the airfoil. The self-excited oscillation of the flap in this region is, therefore, quite complicated, and even at the present stage of investigation, our knowledge about this instability is far from complete. At the same time, the buzz oscillation is featured by the strong effects of non-linearity of flow. That is, the motion of the flap can not be divergent. But at the final stage, it has a sustained oscillation of a finite amplitude, namely a limit cycle. As far as the authors have known, most of the previous works were focused on this final stage of oscillation, while the present authors are trying to investigate buzz with particular emphasis on the study of the transient state of its growth, namely from the oscillation at small amplitudes up to the limit cycle.

The present report contains the results of the following two kinds of experiment with a two-dimentional airfoil-flap combination model. Experiment 1 is concerned with the optical observations of buzz during its growth by use of a high speed motion camera, when the flap of the model was freely hinged by small ball bearings about its axis. Experiment 2 consists of the measurements of the unsteady hinge moment of the flap at small amplitudes with the same model at subsonic and transonic speeds by adopting a free oscillation method.

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2. Apparatus and Methods of Experiment

The 20 cm×12 cm rectangular intermittent transonic wind tunnel at the Institute of Space and Aeronautical Science, University of Tokyo was used for the present experiment.

The roof and floor walls of the working section were slotted and with 10% opening ratio, while the side walls were solid. The working section expanded by 0.6 degree on each slotted wall to allow for the growth of the boundary layer.

Table 1

Airfoil Section	NACA 64A010
Thickness to Chord Ratio	0.10
Position of Maximum Thickness	0.40 chord
Airfoil Chord	8 cm
Airfoil Span	12 cm
Flap Chord	2 cm
Inner Diameter of Bearing	2 mm
Moment of Inertia of Flap about its Hinge	25.14 $g \cdot cm^2$ (Steel Flap) 8.92 $g \cdot cm^2$ (Duralmin Flap)

The model, which is shown in Fig. 1, was a two-dimensional airfoil-flap combination having NACA 64A010 section, whose geometrical and dynamical dimensions are given in Table 1. The gap between the airfoil and the flap was about 0.5 mm. The Reynolds number based on the airfoil chord was 1.2×10^6 approximately at transonic Mach numbers, which indicated that the boundary layer would be laminar over the large part of the airfoil surface. Therefore, the trip wires of 0.2 mm dia were cemented on both surfaces of the airfoil at 5% chord behind the leading edge in order to make boundary layer turbulent. The airfoil, which was made of steel, was clamped to the side walls at each end by use of steel arms. Its incidence was set to be parallel to the free stream direction.

In Experiment 1, the flap was freely hinged by small steel ball bearings at each end, which were fixed in each glass window. Two flaps of the same section, respectively made of steel and of duralmin, were adopted for this experiment in order to find the effects of frequency parameter. The experiment was concerned with the analysis of the high speed Schlieren pictures for the transient motion of the flap, which were taken by using a high speed motion camera immediately after the quick-acting valve was opened, and included the initiation and the growth of buzz.

In Experiment 2, as is shown in Fig. 2, the flap was elastically supported by cross spring pivots outside of each glass window, the center of which coincided with the hinge line of the flap. The gap between the hinge rod of the flap (=4 mm dia) and the circular hole of each glass window was about 1 mm. For the damping oscillation thin musical wires were used to damp the flap, giving the initial deflection angle as large as 15 degrees. The oscillation was started by cutting the wire quickly. The oscillation of the flap at small amplitudes was recorded on the oscillograph as an electric signal which was transmitted by the strain gages bonded on one of the cross spring pivots. From this record, the unsteady hinge moment of the flap during the convergent or divergent oscillation at small amplitudes was determined at subsonic and transonic Mach numbers. The measured values were also compared with the results for Experiment 1.

Fig. 3 shows the Mach number distributions along the roof slotted wall with the model inside the working section, and the Mach number of the uniform flow upstream of the model in Fig. 3 was defined as the free stream value.

3. Experimental Results

Summary of Lambourne's recent work:

It is apparent by Lambourne's work that buzz can be associated with several types of flow régime, and the particular buzz likely to be encountered depends mainly on the wing section, the incidence and the Mach number. His results are summarized as follows[1]

(A) Flap in subsonic flow with shock waves in front of the hinge. Judging from the correspondence of the onset of buzz to the rapid fall of the static pressure near the trailing edge (a clear indication of the onset of the effects of the shock-induced separation of the boundary layer)[3], he proposed *the hypothesis* that the cyclic coupling between the severity of separation of the boundary layer and the strength of the moving shock wave would be essential to the onset of buzz.

(B) Mixed supersonic and subsonic flow over the flap at one or both surfaces between the hinge line and the trailing edge. Separation has been observed but this *may not be* an essential feature.

(C) Supersonic flow over the entire flap with main shock waves attached to the trailing edge. This type of buzz *would be expected to* correspond to the negative damping of the flap predicted by potential flow theories.

The results for the optical observations—Experiment 1:

Most of the findings which have been obtained from the present experiment are concerned with the buzz in region C, while few have been obtained about the buzz in region B and no instability was encountered with the present model in region A. The reason why the buzz was not encountered in region A is now being sought, but it is not clear at present.

In Fig. 4 and Fig. 5 typical examples of the high speed Schlieren pictures for the buzz in region C are shown.

Fig. 4 shows the buzz for the model with a duralmin flap, the Mach number being 1.18 and the film speed being 3600 f.p.s. approximately. With the operation of the quick-acting valve the time required for steady flow at $M=1.18$ to be established in the working section was about 0.25 second. At the flap was freely hinged by bearings at each end in this experiment, it was feared that the flap would start to oscillate before the uniform free stream was established in the working section. However, the Schlieren pictures, which revealed the succesive motion of the flap after the tunnel starting indicated that the oscillation started after the constant free stream was already obtained ahead of the model. This was confirmed by both the observation of the change of flow pattern around the airfoil and the result that the frequency of oscillation at small amplitudes was nearly constant.

At small amplitudes, the shock waves were remained attached to the trailing edge and the supersonic flow was extended over the whole surface of the flap. The considerations that the section of the flap was wedge-shaped and that the disturbance wave produced at the hinge was a straight line indicate that the flow was nearly uniform and parallel to the surface of the flap. The Mach angle of this wave was 50 degree at zero flap angle, by which the Mach number of the flow immediately ahead of the hinge was calculated to be 1.30. This numerical value coincided with the Mach number $M=1.32$ which was determined by the deflection angle of the shock wave ($=60$ degree) and the turning angle of the flow ($=6$ degree) at the trailing edge. Fig. 4 also shows how the amplitude of the flap angle grows from small value. First, this indicates that the type of buzz in this region has a soft oscillator characteristics. Secondly, as the shock waves were attached to the trailing edge during the oscillation at small amplitudes and the effect of boundary layer is not considered to be involved, it is concluded that the negative damping of the motion of the flap is due to the characteristics of the potential flow.

When the amplitude of oscillation exceeded approximately 15 degrees, the disturbance waves produced at the hinge became strengthened and curved. With further increase of amplitude, these waves began to move backwards and forwards over the surface of the airfoil The severe separation of the boundary layer was also observed at the feet of these waves. The amplitude of the limit cycle for this example was about as large as 29 degrees.

Fig. 5 shows an example of the buzz for the model with a steel flap. The flow pattern around the flap was almost the same as in Fig. 4, but as compared with the case in Fig. 4, the frequency of oscillation was decreased due to the increase of the moment of inertia of the flap, and the amplitude increased as large as 40 degree.

At large amplitudes, as is known by the examples in Fig. 4 and Fig. 5, the shock waves reflected from the slotted walls and impinged again upon the surfaces of the flap, which is a clear evidence of the existence of the wall interferences. However, as they were not observed at small amplitudes, it can be concluded that the effects of the roof and floor walls at least on the flow over the surfaces of the flap do not substantially exist during the small oscillations.

Fig. 6 shows the variations in time for the flap angle and the locations of the shock waves which were obtained through the readings of the Schlieren pictures. The wave form of the flap angle is sinusoidal at small amplitudes, whereas distortion is clearly seen at large amplitudes. The movements of the shock waves lag by 30~35 degree behind the motion of the flap, the value being almost unchanged with the increase of amplitude.

In Fig. 7 the variations of the amplitude and the frequency of the flap angle with time are shown. The amplitude grows exponentially with time at small amplitudes, and then the rate of growth increases rapidly and finally slows down. The frequency of oscillation, which is constant at small amplitudes, abruptly decreases, corresponding to the change of growth in amplitude. The initiation of the movements of the shock waves in the Schlieren pictures corresponds to the non-linear changes of these quantities.

When the flow was started at lower Mach numbers, the shock waves, which were attached to the trailing edge at zero flap angle, began to move over the surfaces of the flap even at small amplitudes. The boundary layer separation at the feet of the shock waves is observed in the Schlieren pictures, which are shown in Fig. 8. It is expected, however, that the effects of the flow separation would be small in this region, and the potential flow over the larger part of the surfaces of the flap would be mainly concerned with the onset of the self-excited oscillation, though further experimental verification is needed for this statement. The flow pattern at large amplitudes was the same as those in Fig. 4 and Fig. 5.

With further decrease of the Mach number of the free stream, a buzz having rather irregular wave forms such as is shown in Fig. 9 was observed, and considered to belong to the type of buzz in region B. The motions of shock waves were also very irregular and, although the airfoil was symmetric and its incidence was made zero, the mean flap angle was sometimes not zero due to uncontrolled causes. The wave form of the flap angle, though periodical, was not sinusoidal, and in some cases sudden changes of the mean flap angle occurred. Schlieren pictures show the existence of the severely separated flow behind the feet of the shock waves, but it is still uncertain whether it would be essential to the onset of the buzz in this region. Most of these characteristic behaviors of the motion of the flap in this region coincide with those which have already been pointed out by Lambourne, and few can be added to his findings from the present experiment for the type of buzz in this region.

Measurement of unsteady hinge moment and comparison with theory:

The flow around the flap during the small oscillation in region C, as was stated before, satisfies the conditions of supersonic small disturbance potential flow. Under these conditions and also taking into consideration that the section of the flap was wedge-shaped, it can be said that the motion of the flap is quite similar to the oscillation of a flat plate with zero thickness in supersonic potential flow; in other word, the linearization for the flow field for the present experiment is expected to be valid, although the Mach number of the free stream may be close to one and the reduced frequency may be very small.

According to the unsteady linearized theory for two-dimensional supersonic flow, it is well known that a wide range of negative damping exists with the pitching oscillation of a flat plate for small values of reduced frequency.

In case of

$$\frac{2kM^2}{M^2-1} \ll 1, \qquad (1)$$

the aerodynamic stiffness and damping coefficients of pitching moment, h_β and $-h_{\dot\beta}$ with the axis at the leading edge are given by the following approximate forms[4].

$$-h_\beta=\frac{1}{\sqrt{M^2-1}} \tag{2}$$

$$-h_{\dot\beta}=\frac{1}{\sqrt{M^2-1}}\frac{2}{3}\left(2-\frac{M^2}{M^2-1}\right) \tag{3}$$

It is readily known that the right hand term of (3) is negative for $1\leqq M\leqq\sqrt{2}$, which shows the possibility of the existence of pure pitching flutter in this range. It would be interesting to compare numerically the experimental results with the theoretical values which are given by (2) and (3).

The motion of the flap during the small oscillation for Experiment 1 is expressed simply by the following equation.

$$I\ddot\beta=H=\rho V^2C_F^2s\left(h_\beta\beta+\frac{C_F}{V}h_{\dot\beta}\dot\beta\right) \tag{4}$$

where I is the moment of inertia of the flap about the hinge, and H is the unsteady aerodynamic hinge moment acting the flap. In this case, the frictional torque of the bearings which hinged the flap is neglected, on the assumption that it would be much smaller than the aerodynamic loads.

Thus, h_β and $-h_{\dot\beta}$ at small amplitudes of oscillation can be determined through the measurement of the frequency and the increment of amplitude with the wave form of the flap angle.

The unsteady hinge moment of the flap can also be obtained by use of the free oscillation method. In consideration of the rigidity of cross spring pivots about the hinge and the structural damping of the system, the equation of motion of the flap for Experiment 2 is written as follows.

$$I\ddot\beta+l_\beta\{1+g_\beta\,\mathrm{sign}\,(\dot\beta)\}\beta=H=\rho V^2C_F^2s\left(h_\beta\beta+\frac{C_F}{V}h_{\dot\beta}\dot\beta\right) \tag{5}$$

Table 2

Model Number	No. 1	No. 2	No. 3	No. 4
Moment of Inertia of Flap about its Hinge	61.17 g·cm²	〃	〃	〃
Length×Width of Cross Spring Pivot	13mm×6mm	〃	〃	〃
Thickness of Cross Spring Pivot	0.2 mm	0.3 mm	0.4 mm	0.5 mm
Still Air Frequency of Flap-Cross Spring Pivot System	29.7 c/s	52.5 c/s	76.0 c/s	109.4 c/s
Structural Damping of Flap-Cross Spring Pivot System	0.0172	0.0065	0.0071	0.0097

The dynamic quantities of the model for Experiment 2 are shown in Table 2; the airfoil was the same as used for Experiment 1.

The experiment was conducted at subsonic and transonic speeds for different values of reduced frequency which could be obtained by changing the still air frequency of the system by adopting cross spring pivots with different rigidities. In both experiments, however, the numerical values of k were very small in the transonic region. At high subsonic speeds, the data reduction by the free oscillation method was impossible due to the large distortion of the wave forms.

In Fig. 10 (a) and (b) the variation of both coefficients, h_β and $-h_{\dot\beta}$, with k were small at least for the range obtained in the present experiment. At supersonic Mach numbers, the absolute volues of the aerodynamic stiffness coefficient h_β were much larger than those at subsonic Mach numbers. This is expected to correspond to the local extension of supersonic flow over the surfaces of the flap. The values of h_β were nearly constant at supersonic speeds.

In Fig. 10 (b) the values of $-h_{\dot\beta}$ were positive at subsonic speeds, while at supersonic speeds they became negative. Their values were also nearly constant at supersonic speeds as well as those of h_β.

The dotted lines in Fig. 10 (a) and (b) are the linear-theoretical curves for flat plate, which show the apparent discrepancies between theory and experiment. However, before making a direct comparison between the two, it should be considered that the Mach number of the flow immediately ahead of the hinge is more suitable as a reference Mach number than the real value of the free stream, and for a reduced frequency $\frac{\omega C_F}{2V}$ based on C_F, the chord of the flap is more convenient than the airfoil chord. The reason for this is that the more important region of negative damping is associated with sonic and supersonic flow and under these conditions the calculated airloads due to rotation of the flap are independent of the extent of the fixed portion of the airfoil ahead of the flap.

The Mach number of the flow immediately ahead of the hinge in Fig. 4 and Fig. 5 was about 1.30. On this basis, the agreement of the aerodynamic damping coefficient $-h_{\dot{\beta}}$ between theory and experiment is fairly good, while the experimental values of the aerodynamic stiffness coefficient h_β were somewhat lower than the theoretical one.

Linear theory states that the range for negative values of $-h_{\dot{\beta}}$ is $1 \leqq M \leqq \sqrt{2}$. Unfortunately, however, the Mach numbers in Fig. 4 and Fig. 5 were the highest that could be obtained in this experiment, so that the validity of the theoretical upper boundary for this range could not be examined in the present experiment. It would be interesting to do this through further experiments, in which, for example, the higher free stream Mach number would be obtained by substitution of the transonic test section for supersonic nozzle liners.

As it has now been confirmed experimentally as well as theoretically that the negative damping of rotation of the flap in two-dimensional low supersonic potential flow is possible, the explanation for this can be made as follows: the buzz in this region would be simply due to the existence of the delay of propagation of pressure signal which is produced in nearly sonic flow. The negative damping moment is produced mainly because the aerodynamic restoring hinge moment in steady flow would lag behind the motion of the flap due to this cause.

From the same reason, therefore, we should expect as well the existence of the pure pitching flutter of an airfoil about an appropriate axis in this flow régime. In fact, the present authors have confirmed this statement by other wind tunnel experiments, some of which have already been published[5].

Wind tunnel wall interferences:

No corrections were applied to the data that were obtained in the present experiment. However, due to the large ratios of the chord and the thickness of the model to the height of the working section, wall interferences could not be avoided. For example, the variation of h_β with the Mach number in Fig. 10 (a) indicates that the large blockage interference existed and the Mach number freeze near $M=1$ occurred at rather higher Mach numbers. Holder[6] has stated that in some cases, the flow in the slotted test section is similar to that in the open jet, and in the presence of a model, the value which is determined as the free stream Mach number by measurement of the static pressure distribution along the roof or the floor wall, may often be larger than the correct one.

4. Conclusions

1. The experimental investigations on control-surface buzz were conducted with a two-dimensional airfoil-flap combination model at the 20cm×12cm rectangular intermittent transonic wind tunnel of the Institute of Space and Aeronautical Science, University of Tokyo.

2. Buzz with the shock waves ahead of the flap was not encountered in the present experiment. The reason for this is not clear at present and it needs further study.

3. It was found that for the buzz with the shock waves over the surfaces of the flap the wave form of the flap angle was not sinusoidal, and in some cases sudden changes of the mean flap angle happened. These results have coincided with the findings which have already been obtained by Lambourne.

4. When the shock waves were attached to the trailing edge, the observed buzz had the characteristics of a soft oscillator in which the amplitude of the flap angle grew from small value. At small amplitudes, the effects of boundary layer were not observed, and this type of buzz was found to be associated with the characteristics of low supersonic potential flow. However, at large amplitudes the shock waves moved backwards and forwards over the

surfaces of the airfoil and the severe separation of boundary layer was also observed

5. The aerodynamic damping coefficient of the unsteady hinge moment which was abtained by the analysis of divergent oscillation of the flap was in fair agreement with the value predicted by the two-dimensional linearized unsteady flow theory in low supersonic region, when compared on the basis of the local Mach number over the flap.

5. Acknowledgements

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List of Symbols

M Mach number
V Velocity
ρ Air density
β Angular deflection of flap (temporarily used as angle of attack in equations (2) and (3))
β_0 Mean angular deflection of flap
c Airfoil chord
x Distance measured from the hinge
C_F Flap chord
s Airfoil span
α Angle of attack
S_1 and S_2 Positions of shock waves
I Moment of inertia of flap about its hinge
H Aerodynamic unsteady hinge moment
h_β Aerodynamic stiffness coefficient of unsteady hinge moment about the hinge (temporarily used as that of unsteady pitching moment about the axis at the leading edge in equation (2) and (3))
$h_{\dot\beta}$ Aerodynamic damping coefficient of unsteady hinge moment about the hinge (temporarily used as that of unsteady pitching moment about the axis at the leading edge in equations (2) and (3))
k Reduced frequency $\left(=\frac{\omega C_F}{2V}\right)$
l_β Rotational rigidity of cross spring pivots
g_β Structural damping
ω Frequency (rad/sec)

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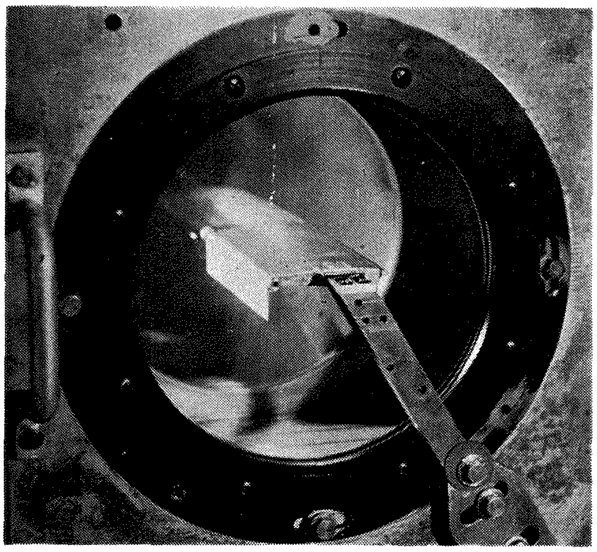


Fig. 1 Airfoil-flap combination model for Experiment 1

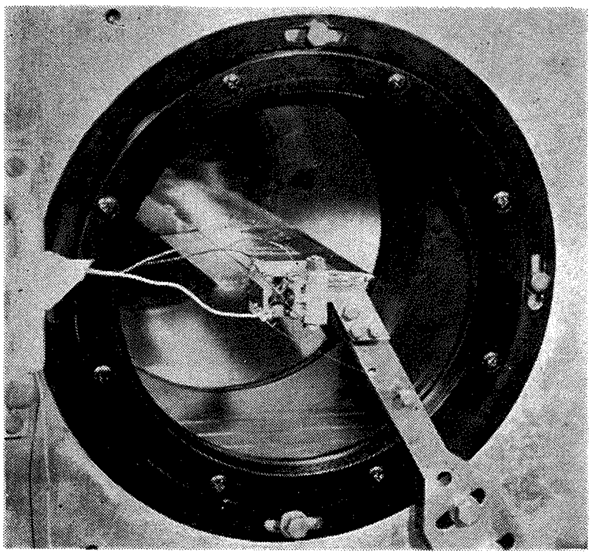


Fig. 2 Airfoil-flap combination model for Experiment 2

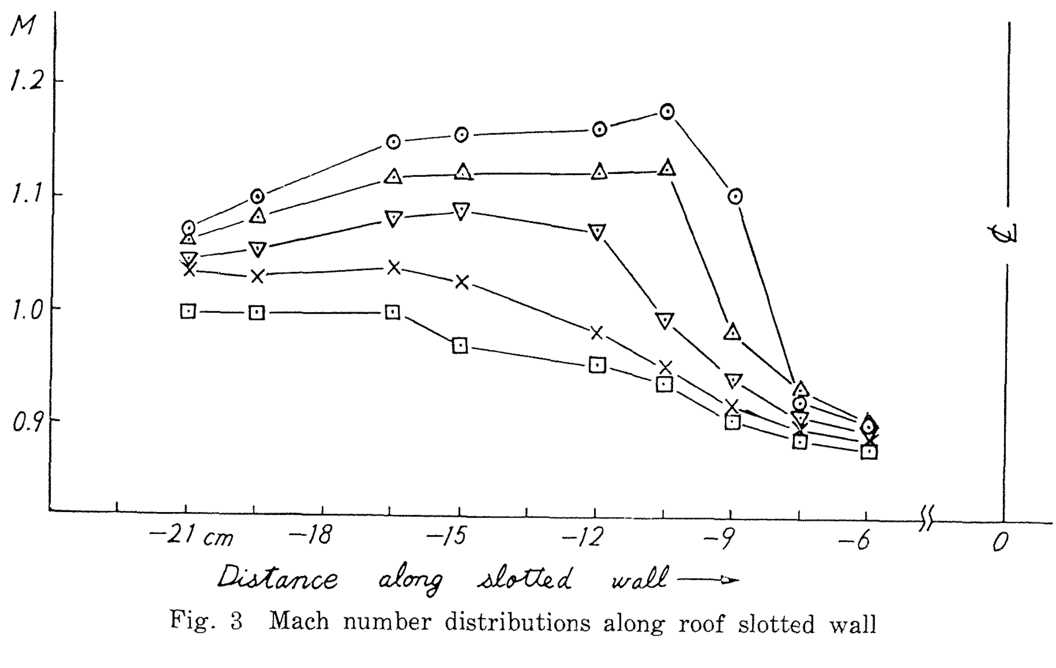
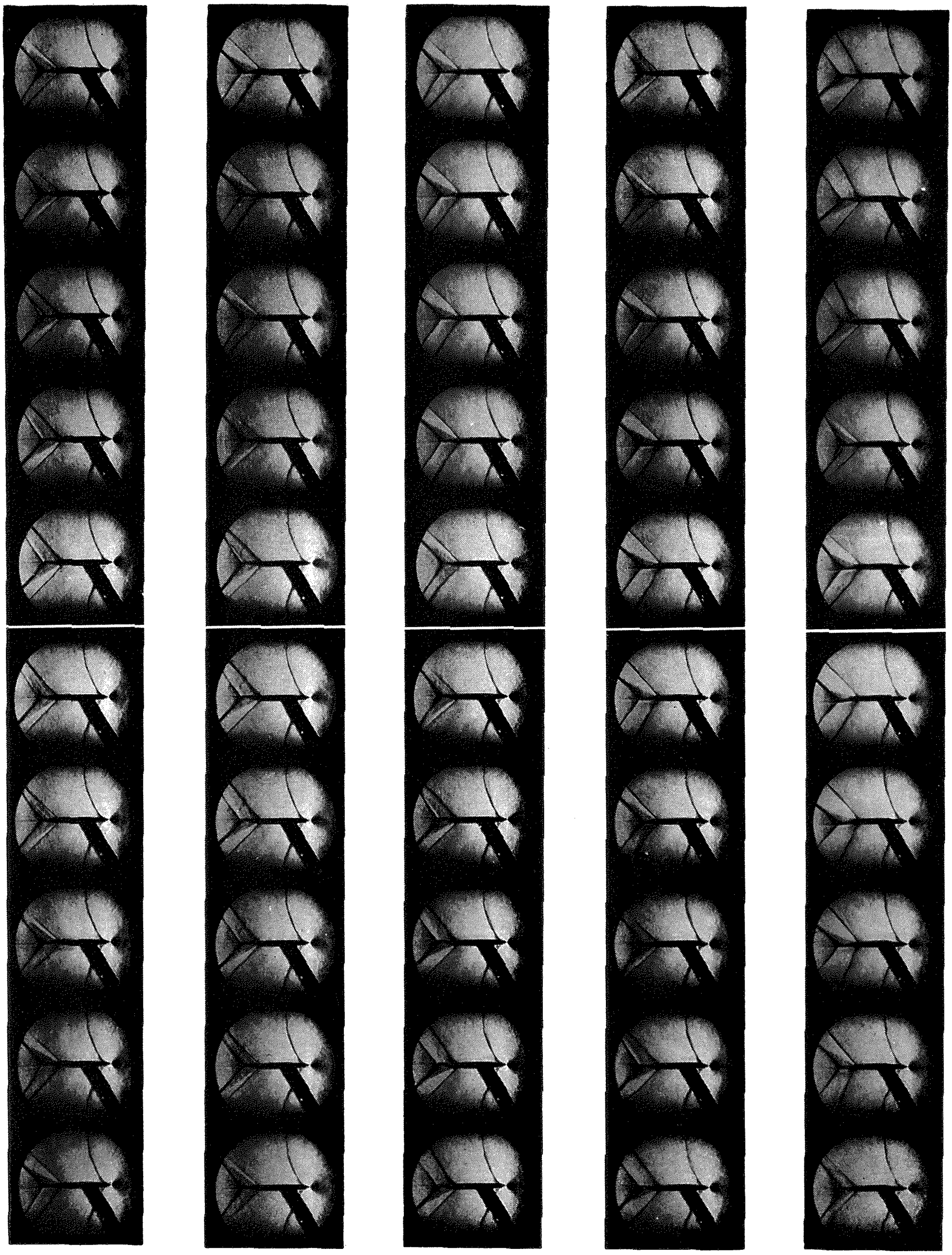
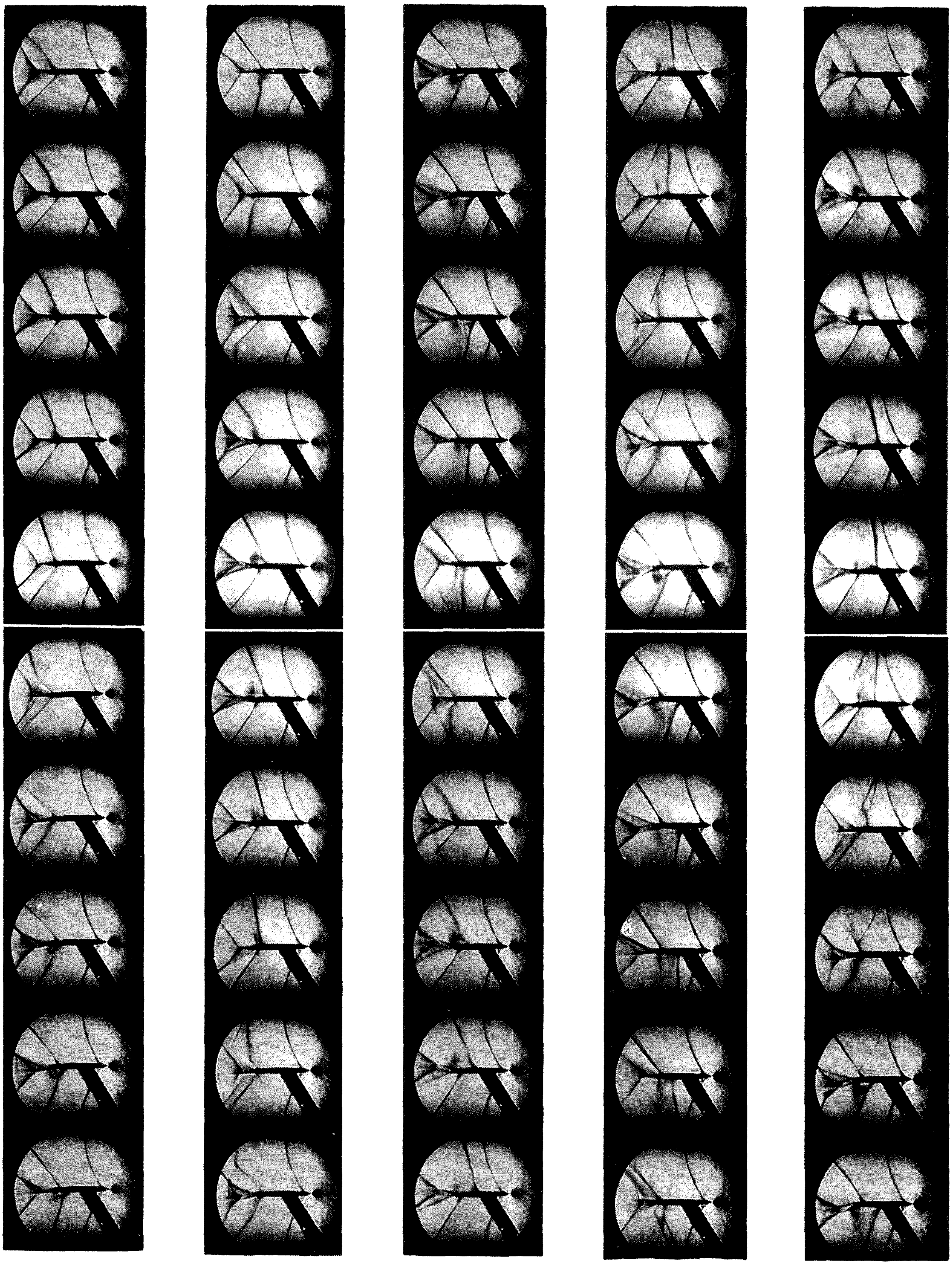


Fig. 3 Mach number distributions along roof slotted wall



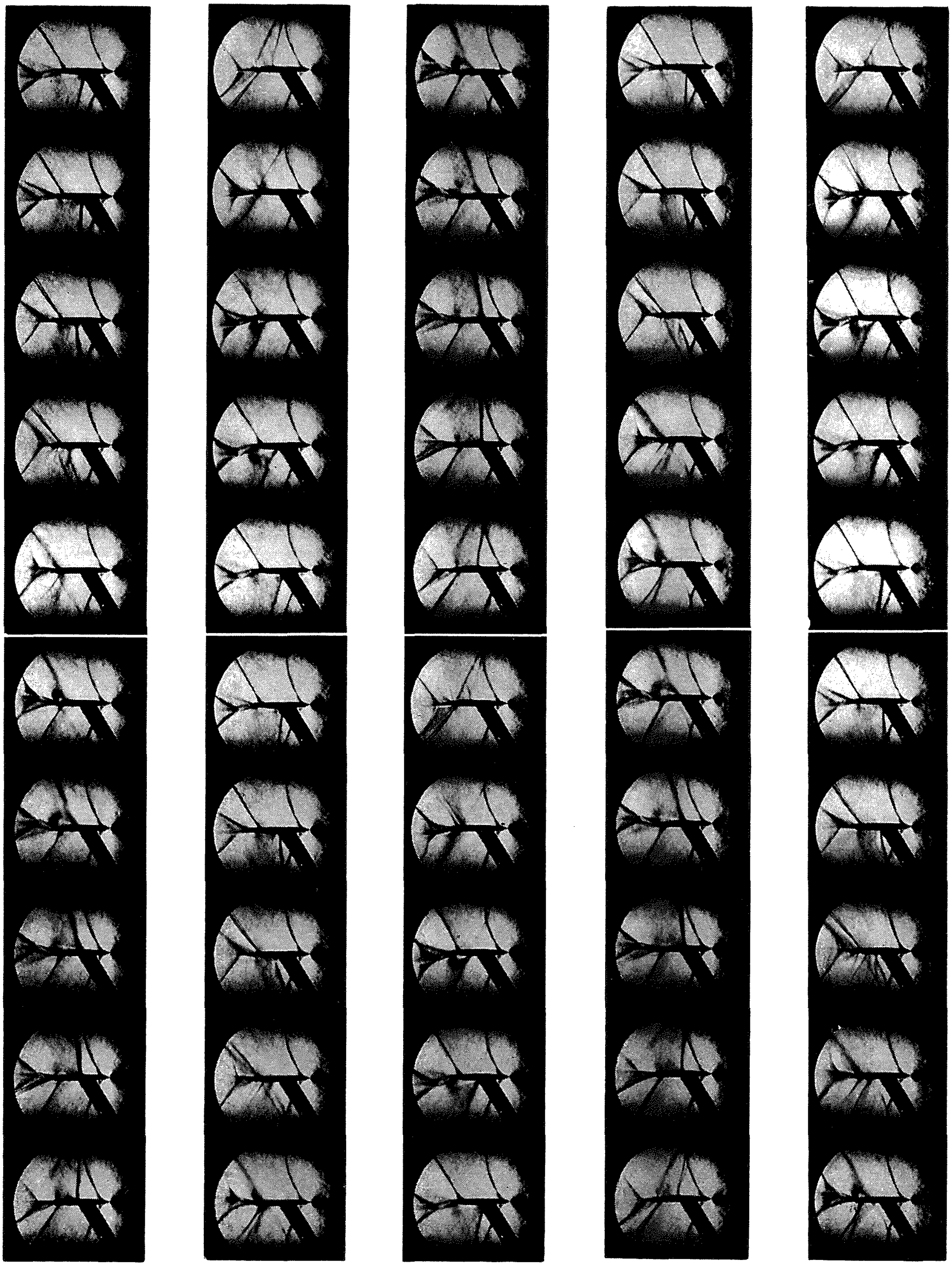
1~2 3~4 5~6 7~8 9~10

Fig. 4 (1)



11～12 13～14 15～16 17～18 19～20

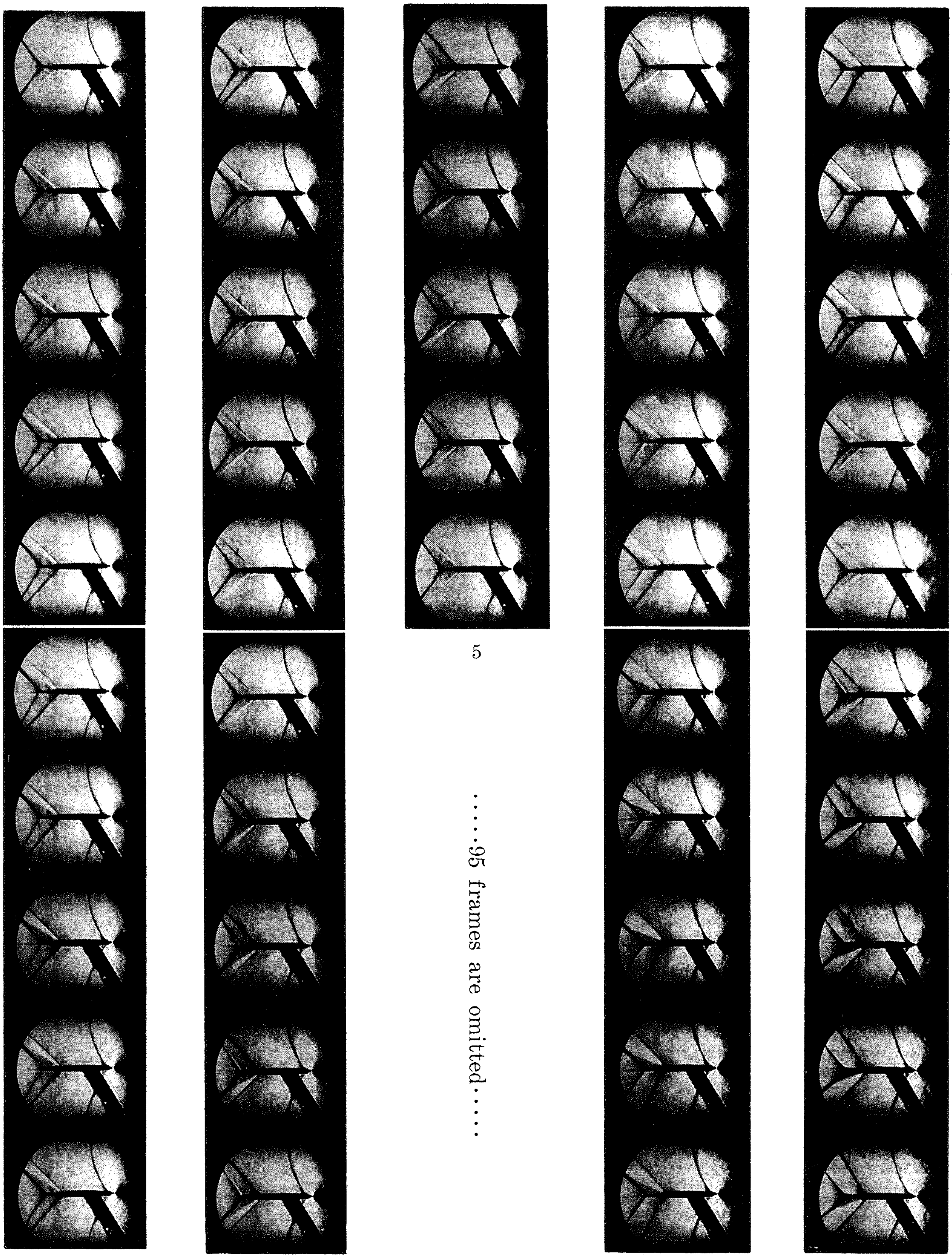
Fig. 4 (2)



21~22 23~24 25~26 27~28 29~30

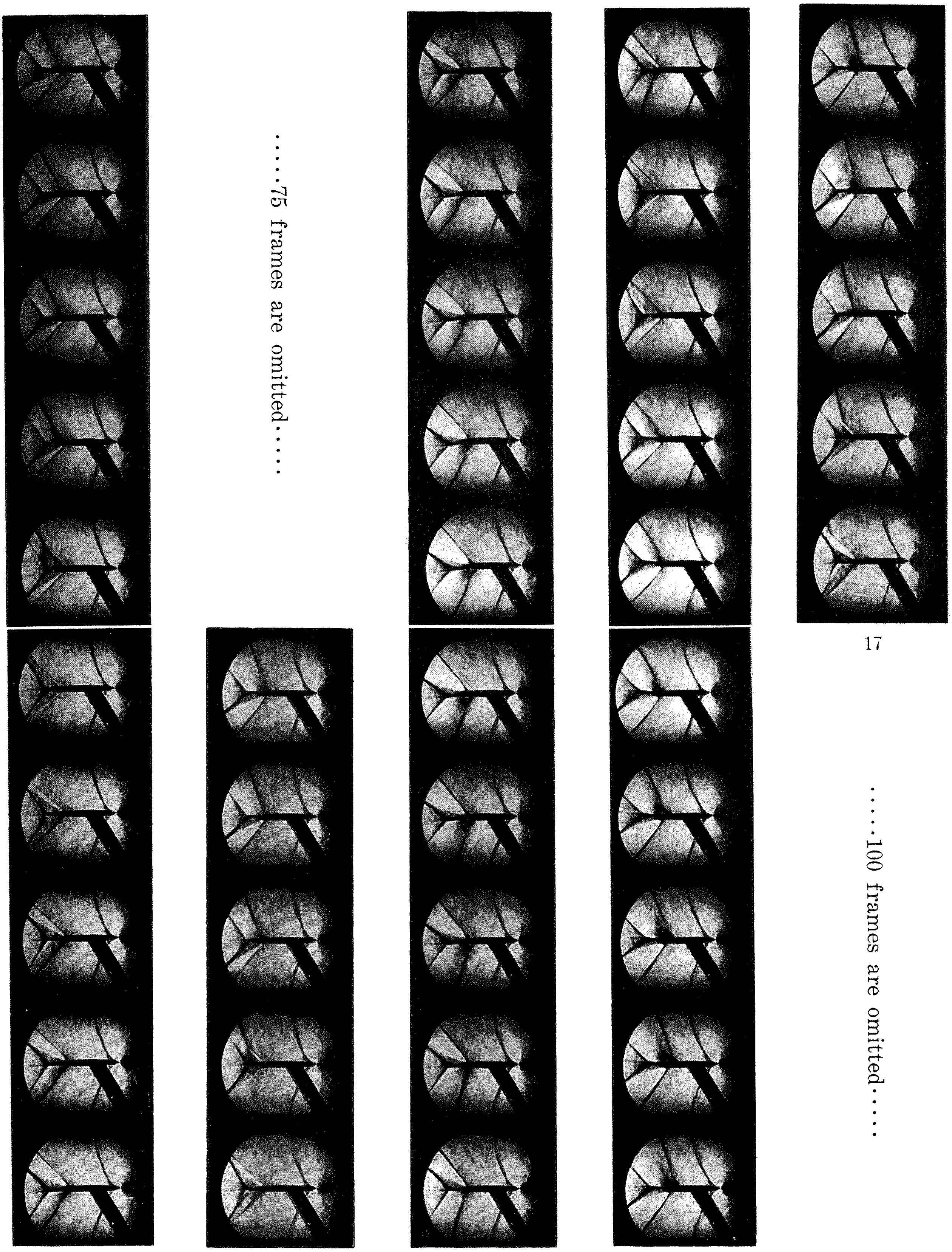
Fig. 4 (3)

High speed Schlieren pictures showing the growth of buzz
$M=1.18$ Incidence 0° Duralmin flap
Film speed 3,600 f.p.s. (approx)



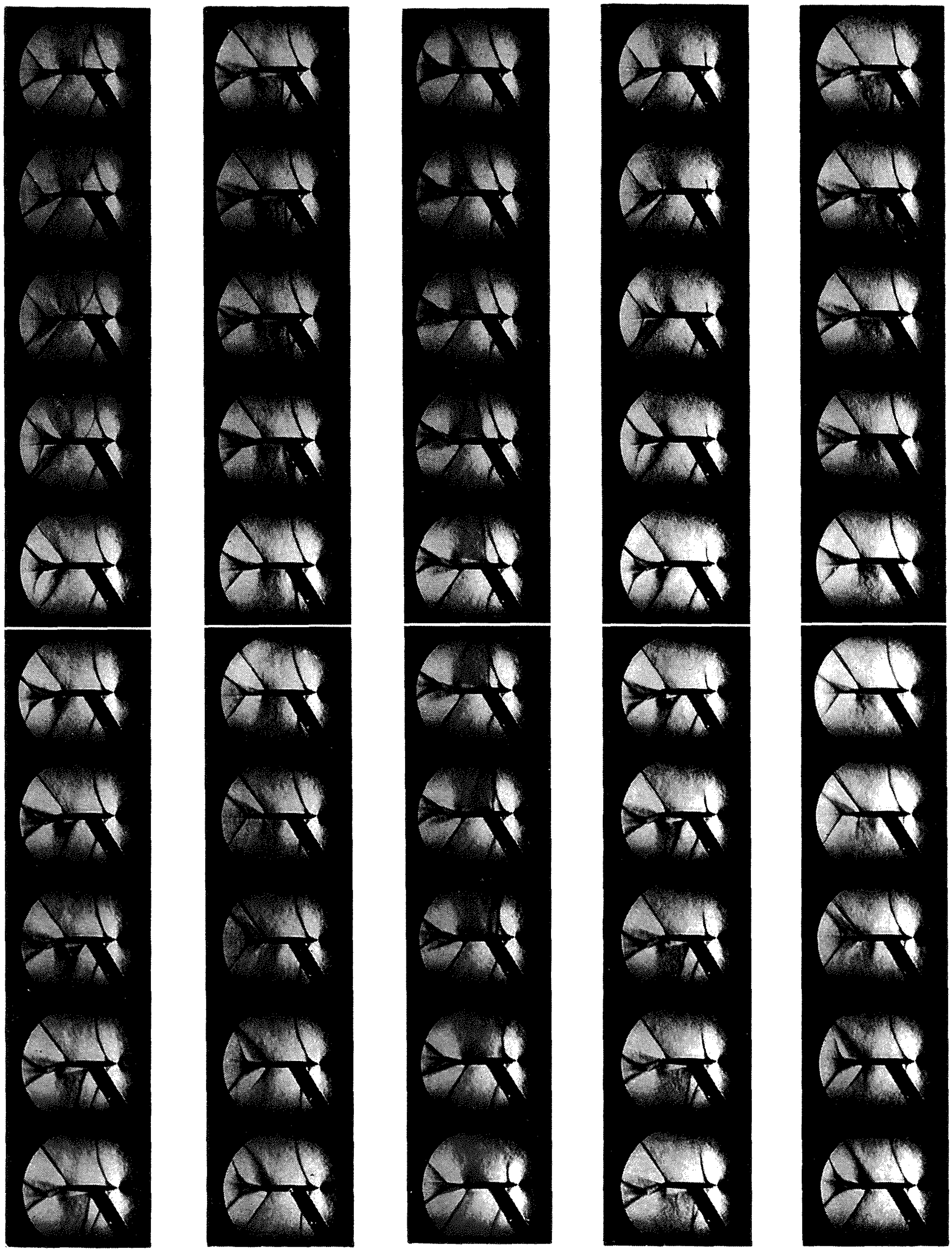
1~2 3~4 6~7 8~9

Fig. 5 (1)



10~11 12 13~14 15~16

Fig. 5 (2)



18~19 20~21 22~23 24~25 26~27

Fig. 5 (3)

High speed Schlieren pictures showing the growth of buzz

$M=1.15$ Incidence 0° Steel flap

Film speed 4,200 f.p.s. (approx)

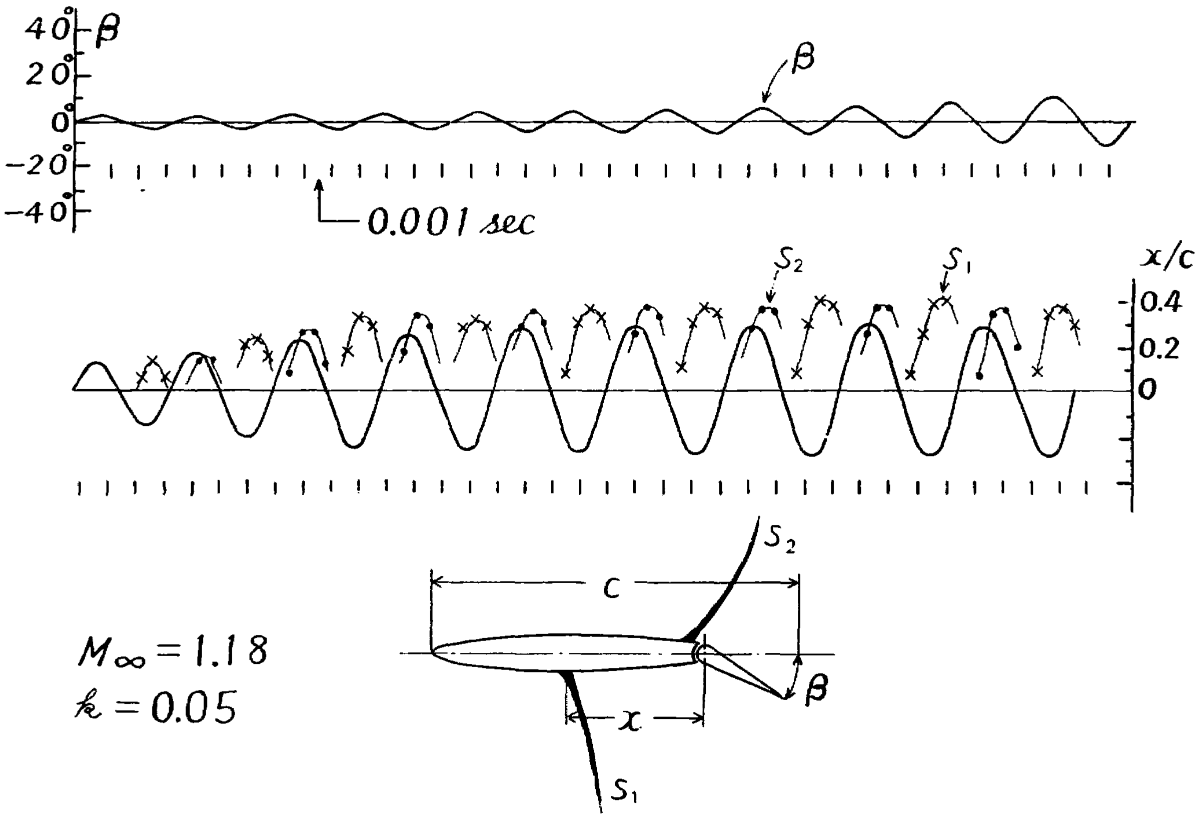


Fig. 6 Wave forms of flap angle and locations of shock waves during the growth of buzz

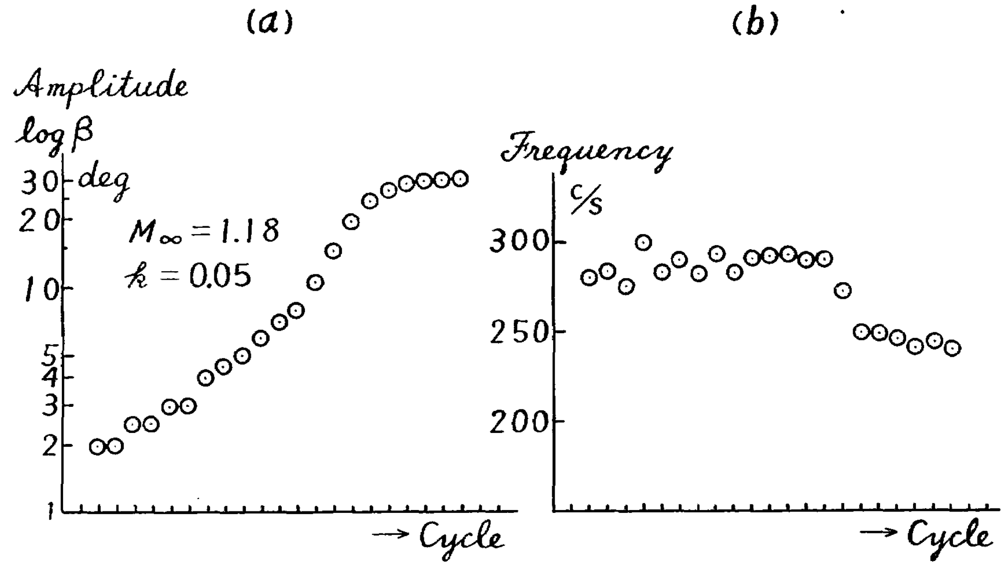
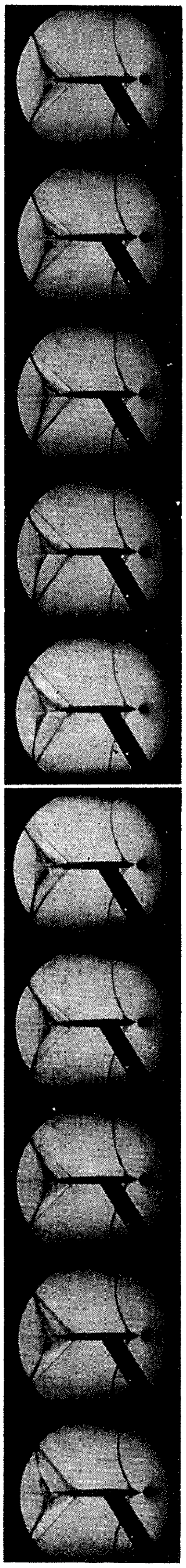
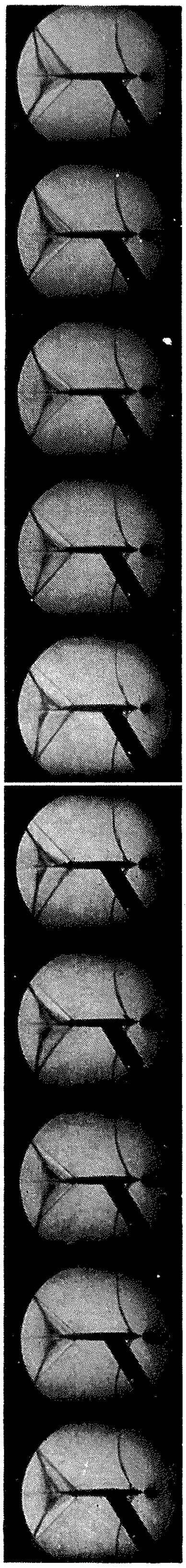


Fig. 7 Variations of amplitude and frequency during the growth of buzz

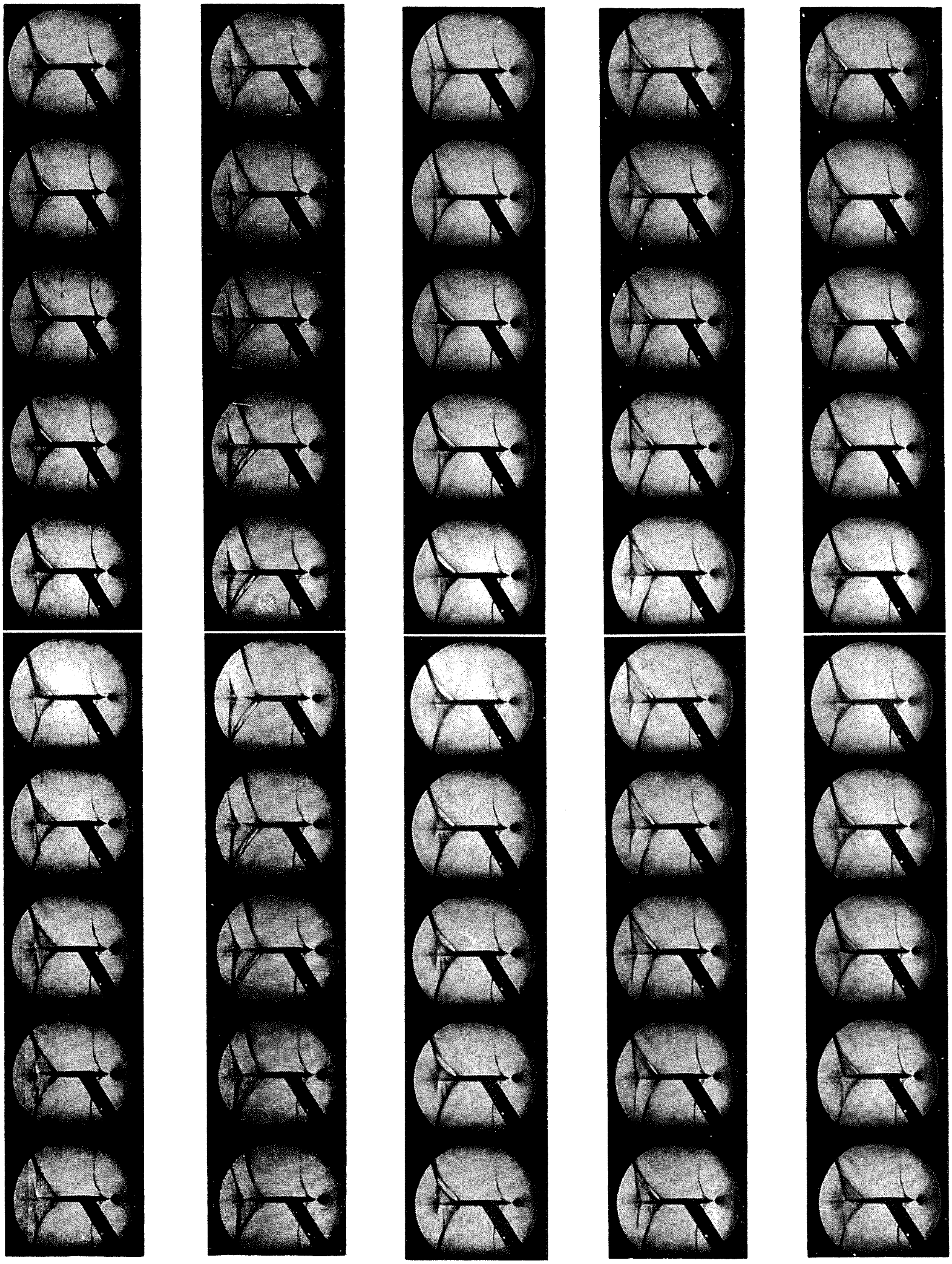


1~2



3~4

Fig. 8 Buzz oscillation at small amplitude at $M=1.08$
Duralmin flap Incidence 0° Film speed 2,400 f.p.s. (approx)



1~2 3~4 5~6 7~8 9~10

Fig. 9 Buzz oscillation at $M=1.04$ Steel flap Incidence 0°
Film speed 4,600 f.p.s. (approx)

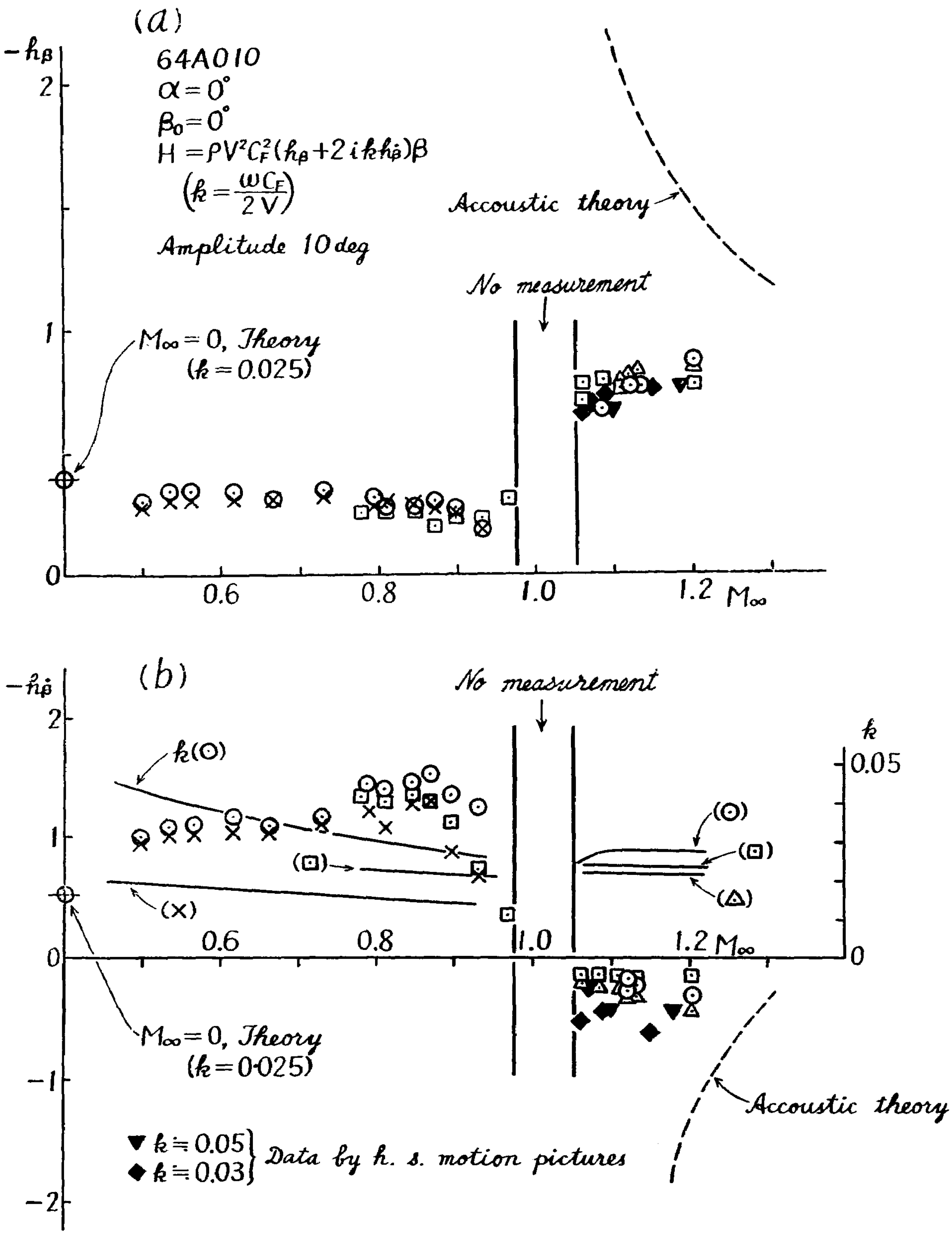


Fig. 10 Unsteady hinge moment coefficients of the flap at subsonic and transonic Mach numbers

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