THE FLUTTER MECHANISM OF SHEET

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ABSTRACT

Basic study has been conducted on sheet flutter which becomes an obstacle to the operation of printing machines and paper making machines in higher speed. Following three topics are presented in this paper.

(1) Fluctuating pressure causes sheet flutter. This fluctuation occurs as the vortex separates at the leading edge of the sheet and grows toward the downstream corresponding to the sheet movement.

(2) Characteristics of sheet flutter were clarified with respect to the following points.
(a) Flutter mode, (b) Flutter amplitude, (c) Flutter frequency, (d) Influence of damping factor

(3) The critical velocity of sheet flutter is determined by the following three parameters.
(a) Aspect ratio (b/c), (b) Rigidity parameter ($Eh^3/12\rho_A c^3$), (c) Mass ratio ($\rho_P h/\rho_A c$)
(where b = sheet width, c = sheet length, h = sheet thickness, E = Young's modulus,ρ_P= Sheet density,ρ_A= Air density)

NOMENCLATURE

a	Amplitude	(m)	(mm)
c	Sheet length	(m)	(mm)
C_d	Drag coefficient		
C_l	Lift coefficient		
E	Young's modules of sheet	(N/m^2)	
g	Structure damping coefficient		

h	Thickness of sheet	(m) (mm)
$h(t)$	General coordinate	(m)
I	Second moment of sheet area ($= 1/12h^3$)	(m^3)
p	Circular frequency	(H_z)
q	2π/wave length	(1/m)
S	Rigidity Parameter	(m^2/s^2)
t	Time	(s)
V	Flow velocity	(m/s)
w	Out-of-plane displacement of sheet	(m)
X	Flow direction coordinate	
α	Exponent	
ρ_A	Air density	(Kg/m^3)
ρ_P	Sheet density	(Kg/m^3)
μ	Mass Ratio	
$\phi(x)$	Mode function	

SUBSCRIPTS AND SUPERSCRIPTS

*	Non-dimensional value
Q	Value of quenching point of flutter
S	Value of self-starting point of flutter

PREFACE

Problems caused by paper flutter have arisen in paper making machinery and in printing presses as their operating speed has increased. Followings are some examples of the problems.

(1) Folder on a rotary press may cause edge breakage of the sheet. Fig.1 illustrates the folding process and the problem. While a sheet is folded in an area between folding cylinder and gripping cylinder,flutter occurs and sheet collides with the guide plate or the gripper cylinder,which results in the sheet breakage.

(2) Flutter causes miss-registration in printing process and miss-operation of the crinkle detecting sensor in the sheet fed press.

(3) Flutter causes web breakage and/or wrinkling in a dryer of paper making machinery.

In order to avoid the waste of both materials and time caused by these problems,it is necessary to develop fundamental insights into the paper flutter in which field not many studies has been done.

This paper presents results from our fundamental research on sheet flutter. It contains those from the flutter test and from visualization to clarify characters of the flutter on the rectilinear motion of the sheet. Their flow and mode were examined with a wind tunnel and water tank .

TEST OUTLINE

Table 1 shows tested items. In multi panel model, a curvilinear mode is approximated to a polygonal line, because it is easy to change a parameter (mass ratio, structure damping and rigidity parameter mentioned later) independently on this model. The flutter test using this model is performed for the purpose of clarifying the influence of the parameter. In the flutter test for a paper, the critical flutter velocities are investigated with different sizes of sheets; 9 for paper and 7 for flexible sheets other than paper (vinyl, cellophane, aluminium, etc.) The wind tunnel has measuring section of 1m × 1m × 2.5m (Depth ×width × length) and its maximum wind velocity is 25m/s. (discharge type) The water tank has measuring section of 0.28m × 0.3m × 0.7m and the pass type of maximum velocity is 0.9m/s.

FLUTTER TEST

Parameter Relative to Flutter

Parameters concerning the critical flutter velocity were led with the basic equation of non-dimensional sheet flutter to set test conditions. If two dimensional motion is assumed for simplification, the movement of the sheet in flow is:

$$\rho_P h\frac{\partial^2 w}{\partial t^2} + (1+ig)EI\frac{\partial^4 w}{\partial x^4} = \frac{1}{2}\rho_A V^2 C_d c\frac{\partial^2 w}{\partial x^2} + \frac{1}{2}\rho_A V^2 C_l \frac{w}{c} \tag{1}$$

Equation (1) with non-dimensional values t = t*c/V, w = w*c, x = x*c yields the following equation.

$$\frac{\rho_P h}{\rho_A c}\frac{\partial^2 w^*}{\partial t^{*2}} + (1+ig)\frac{EI}{\rho_A c^3}\frac{1}{V^2}\frac{\partial^4 w^*}{\partial x^{*4}} = \frac{1}{2}C_d\frac{\partial^2 w^*}{\partial x^{*2}} + \frac{1}{2}C_l w^* \tag{2}$$

From equation (2), it is considered that the flutter is influenced by the following parameters against the critical flutter velocity.

$\rho_P h/\rho_A c$: Mass ratio (hereinafter shown as μ)

$EI/\rho_A c^3$: Sheet rigidity for mass of fluid (hereinafter referred to "Rigidity Parameter" and shown as S)

g : Structure damping coefficient.

Aspect ratio b/c is also necessary in analyzing three dimensional motion where b represents sheet width.

In the following flutter test, the character of the critical velocity was investigated by varying these parameters.

Flutter Test of Multi Panel Model

Test Technique.

The two dimensional model of 4 hinges and 4 panels is tested. (hereinafter called as "multi panel model") The top of the model is supported with wire and pipe so that the model can rotate freely. Panels are connected with the wire which has torsional rigidity. Parameters examined are as follow.

Mass : Materials of panels is varied. (Stainless steel, vinyl chloride, foam styrol)

Rigidity : Diameter of wire used for connecting panels is varied. The rigidity of multi panel model is equivalent to that of the flexible sheet with the same primary natural frequency.

Damping : Damping is added by covering the area between panels with vinyl tape

By varying these parameters,μ, S, and g are

μ: 0.0057 - 9.1

S : 1.5×10^{-6} - 6.1×10^{-3} (m^2/s^2)

g : 0.85, 3.4

μ and S shows the value range of all test cases (25 cases).

g is the value of 2 cases to show whether the damping is added or not.

Test Results.

(1) Characters of amplitude and frequency

Two typical examples are shown in Fig. 3. The followings are found with respect to the amplitude and frequency of the sheet flutter. When the flow velocity is gradually increased, the amplitude is rapidly increased at any flow velocity point.(V_S) When additionally increasing the flow velocity, the amplitude becomes steady after merely increasing. When reducing the flow velocity, the amplitude exceeds the point ofV_S and vanishes at the point ofV_Q. This flutter is called a hard flutter. Also,V_S is called a self starting point and V_Q, a quenching point. Next, the frequency is increased in proportion to the flow velocity. It is considered that the tensile force (fluid drag) affecting to the sheet is increased in proportion to the square of the flow velocity.

(2) Influence of damping ratio

Influence of g is investigated. Fig. 4 shows the critical velocity of cases with/without additional damping. The results of the investigation indicates that the influence of the damping ratio on the critical velocity is a little. Thus, in the sheet, it is considered that the structure damping force is excessively weak in comparison with an air damping force because a pressure receiving area is wide in spite of thin sheet and light mass.

(3) Character of critical velocity

Fig. 5 shows relations of V_S and V_Q against the rigidity parameter S. When S is small, V_S and V_Q are in proportion to 1/2 power of S, while V_S and V_Q diverges as the value of S increases. For this, non-dimensional parameters and mass ratio μ are convenient for this discussion as will be mentioned later in this paper. These non-dimensional parameters are expressed with rigidity parameter S.

$$V_S^* = \frac{V_S}{\sqrt{S}} \ , \ V_Q^* = \frac{V_Q}{\sqrt{S}} \tag{3}$$

From Fig. 6, it is understood that μ and S under the sheet flutter critical velocity are greatly influenced.V_S^* and are almost steady to 0.3 of μ. However, if exceeding this value, the critical velocity is suddenly reduced and it may be kept at a low value. In the changing point of this critical velocity, the frequency mode is also varied as mentioned later and the frequency tends to be increased.

Flutter Test of Paper Sheet

Test Technique.

Fig. 7 shows the test technique. The wire is vertically stretched in the wind tunnel and it is covered on both sides with comparatively thick sheets to set the tested sheet into thick sheets. Tested sheets are classified into two kinds, the flag type of an aspect ratio 0.7 and a longitudinal type of the aspect ratio 2.3 to 3.0. The kinds of sheets are as follows.

Paper : 9 kinds of sheets (thickness 25 to 235 (μm). Basis weight 14 to 157 (g/m^2)).

Non-paper : 7 kinds of sheets (2 kinds of plastic, aluminum sheet, 2 kinds of vinyl, copper sheet and cellophane).

The parameter ranges of the flutter test are as follows.

$\mu = 0.012 - 0.97$,

$S = 7 \times 10^{-6} - 1.4 \times 10^{-1}$ (m^2/s^2)

During the test, the flow velocity is gradually increased to measure a self starting pointV_S, and then the flow velocity is lowered to measureV_Q.

Test Results.

Fig. 8 shows the relationship between non-dimensional critical velocities,V_S^* andV_Q^*, and mass ratio μ. This figure shows V_S^* and V_Q^* of the multi panel model with broken lines. This indicates that V_S^* and V_Q^* of the longitudinal type sheet resemble the multi panel model and that the flow velocity is almost steady to any mass ratio (μ_c). V_S^* and V_Q^* of the flag type sheet is large in proportion to the longitudinal type sheet. Its difference is large especially when μ is small. There are some explanation for this.

Critical velocity increases by the aspect ratio effect, which is found in the flutter of the vane.(1)

Fluid drag increases when the aspect ratio is small. This causes increase of tensile force hence increase of critical velocity. (2)

Influence of Re number, defined with the critical velocity and the sheet length, was found to be small. This result agrees with the former study (3) .

FEATURES OF FLUTTER MODE

The frequency mode of the multi panel model sketched from a time-lapse VCR is shown in Fig. 9 and the frequency mode of the paper sheet filmed with a multiple exposure method in Fig. 10. The thin paper sheet is equivalent to a-2 of the multi panel model, and the thick paper to b-2. From these results, there are the following features for the sheet flutter mode.

(1) It is found that a wave motion is a progressive wave.

In the flutter of the vane or a suspension bridge, the amplitude w (x, t) is indicated as the product of a mode function $\phi(x)$ and a general coordinate h (t).

$$w(x, t) = \phi(x) \cdot h(t) \tag{4}$$

Thus, the function is separated to x and t and the wave motion is a stationary wave. While in the sheet flutter, the function is not separated to x and t. Accordingly, it is indicated with the following function. The wave motion is the progressive wave.

$$w(x, t) = ax^{\alpha} \cdot \sin(pt + qx) \tag{5}$$

(2) When the mass ratio μ is larger, the amplitude a is also larger.

(3) When flow velocity is increased, the amplitude of the leading edge becomes a little, sharpening form. (α of the above equation (5) is larger.)

FLOW VISUALIZATION

Flow around Multi Panel Model

The flow around the multi panel model is investigated by applying a hydrogen bubble method for the flutter test into the water tank. The flow sketched from the time-elapse VCR is shown in Fig. 11. The vortex occurring in the upper face is indicated with the broken line and the vortex in the lower face with a solid line. Time elapses in the order of 1, 2 - - - -, 9. 1 and 9 are the same situation, and the time from 1 to 9 is one cycle. The situation is found in which the vortex releases from the leading edge and flows downstream while growing.

Flow around Paper

The flow around the paper visualized with smoke wire method is shown in Fig. 12. The situation in which the vortex occurs at the leading edge and flows the downstream can be seen from this photograph. For judging from the flow around the multi panel model and paper, it seems that fluctuating pressure causes sheet flutter. This fluctuation occurs as the vortex separates at the leading edge of the sheet and grows toward the downstream corresponding to the sheet movement.

SUMMARY

Concerning the sheet flutter, the basic test is performed to discuss the cause of flutter, form, critical velocity, etc. As a result, the followings are clarified.

(1) Sheet flutter is caused by the pressure variation which occurs when the vortex released from the leading edge flows in the downstream and grows by sheet motion.

(2) Features of sheet flutter are as follows.
   (a) The flutter mode is the progressive wave.
   (b) Hysteresis is given on flow velocity and amplitude curve,because starting point of a flutter differs from a stopping point, .
   (c) Damping ratio is almost uninfluenced.
   (d) The flutter frequency is increased in proportion to the wind velocity.

(3) The critical wind velocity of the paper flutter is defined by the following three parameters.
   (a) Aspect ratio
   (b) Rigidity parameter
   (c) Mass ratio

Characteristics of the sheet flutter in rectilinear motion is clarified in the first research of ours. We have plans to extend this research to web, to further study of flutter phenomenon, and to the development of protection device for the actual machine.

REFERENCE

1. Scanlan, R.H., Rosenbaum,R., Introduction to the Study of Aircraft Vibration and Flutter, Macmillan, New York, 1960, pp. 220-222.
2. Hoerner,S.F., Fluid Dynamic Drag, Published by the author, 1958, pp 3-25.
3. Taneda,S. "Drag Force of Fluttering Textile", Proceedings of the 21st Annual Conference, Japanese Society of Physics, 1966.

Table 1 Test item

Model Equip-ment Test item	Multi-panel model	Paper
	Water tank, wind tunnel	Wind tunnel
Flutter test	Critical velocity, and flutter frequency	Critical velocity
Visualization of mode	Observation for VTR	Multiple exposure method
Visualization of flow	Hydrogen bubble method	Smoke wire method

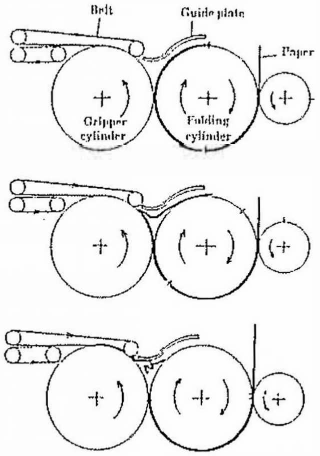


Fig. 1 Sheet behavior in the folder

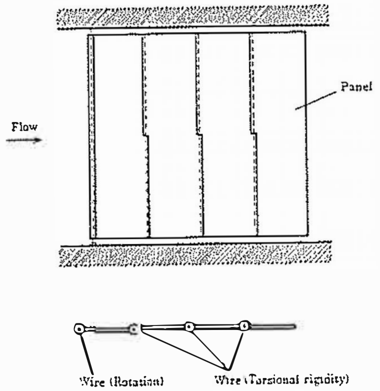


Fig. 2 Test method of multi-panel model

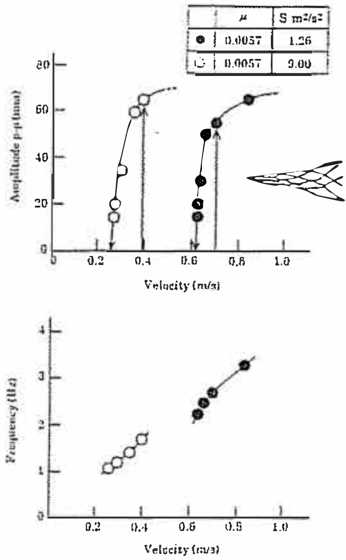


Fig. 3 Effect of amplitude and frequency

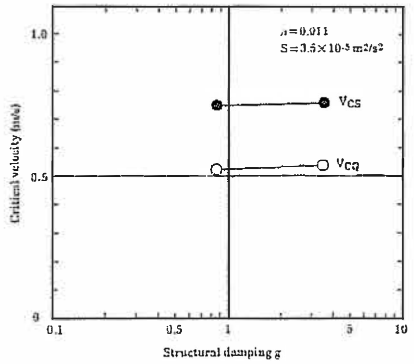
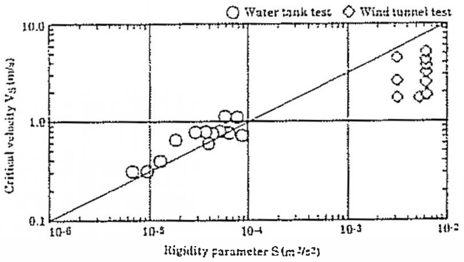
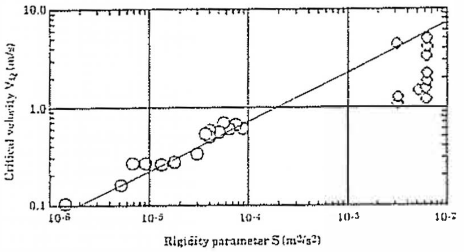


Fig. 4 Effect of structural damping on the critical velocity

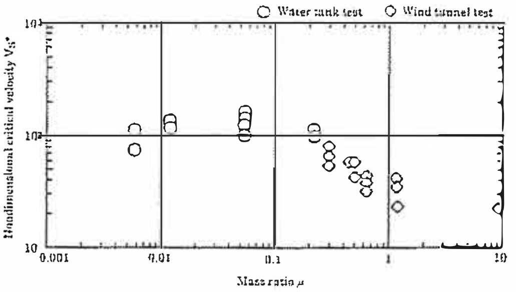


(a) Self starting point

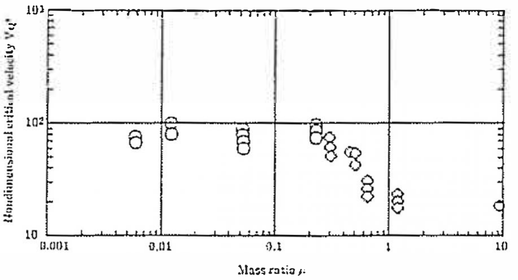


(b) Quench point

Fig. 5 Critical veloctiy of multi-panel model



(a) Self-starting point



(b) Quench point

Fig. 6 Nondimensional critical velocity of multi-panel model

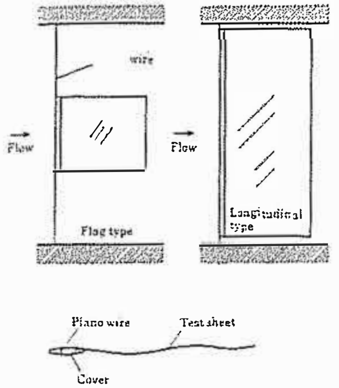
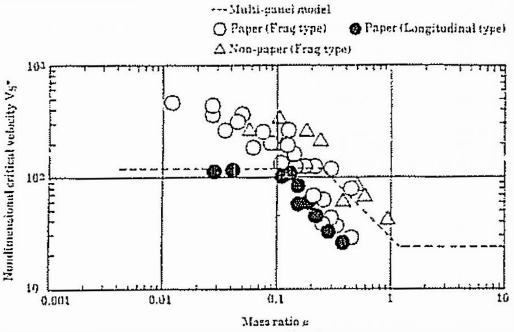
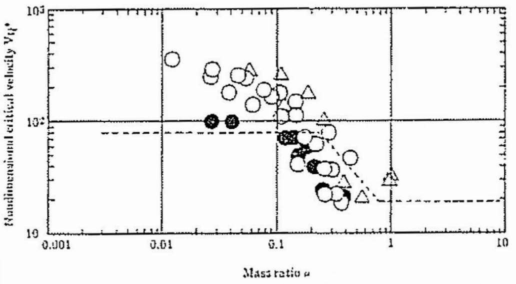


Fig. 7 Test method of sheet flutter



(a) Self starting point



(b) Quench point

Fig. 8 Nondimensional critical velocity of paper

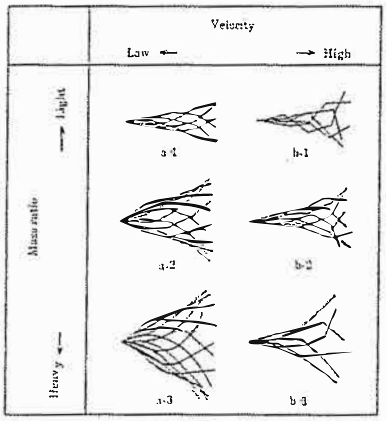
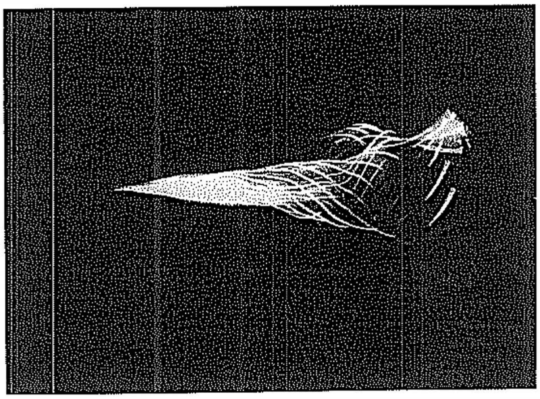
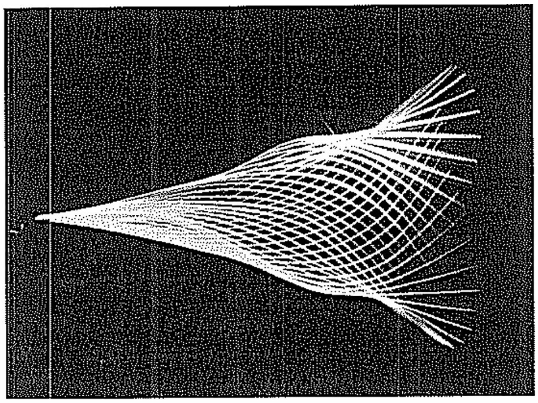


Fig. 9 Flutter mode of multi-panel model



(a) Small mass ratio paper



(b) Heavy mass ratio paper

Fig. 10 Flutter mode of paper

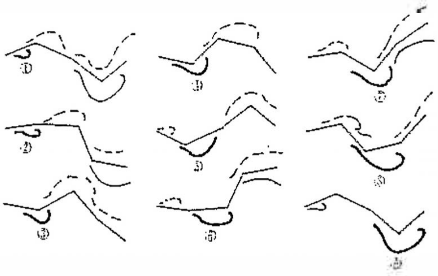


Fig. 11 Flow around fluttering multi-panel model

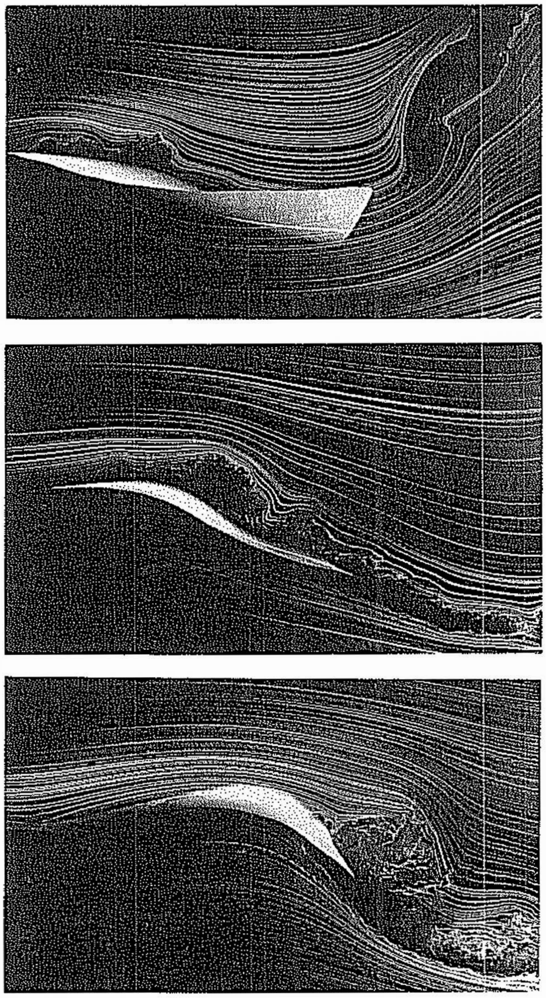


Fig. 12 Flow around fluttering paper

THE FLUTTER MECHANISM OF SHEET

S. Suzuki

What were typical values of V_S?
Tim Walker, 3M

4 to 10 meters per second.

Your conclusion that the vortex formation caused the flutter is applicable to your test of the short web. How would that change for a continuous web?
Dr. Frank Chambers, Oklahoma State University

Continuous webs have two simply supported edges with tension applied. The discrete sheets which I used have only the top of the sheet supported. The paper which follows by Chang and Moretti is more representative of the continuous web.