EDGE FLUTTER IN WEBS

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ABSTRACT

A persistent problem in paper machines and other webs subjected to drying air flows is edge flutter. The resulting stresses can damage the edges, initiate tears and breaks in paper machines, or spoil coatings near the edges of polymer webs.

Analytical and experimental studies showed that the interaction of the web with the surrounding air is an important part of the problem, especially if there is a cross-machine flow component. This interaction has been investigated in wind tunnel tests. The results have been plotted to separate the influence of each design parameter on the incidence and severity of flutter. Semi-empirical equations have been developed to assist in the prediction of critical conditions. They should be helpful in selecting operating conditions, and avoiding either excessive or insufficient tension.

A number of practical suggestions are made for managing the drying air flow in order to minimize flutter damage.

INTRODUCTION

Web flutter is a serious obstacle to high-speed operation of web-manufacturing machines. It can cause quality problems or breaks in the web. Web flutter is a complicated phenomenon caused by an improper combination of operation parameters: machine speed, air flow, web tension, basis weight, etc. One feature of web flutter is the vibration of free edges (edge flutter) of a web that might be caused by cross-machine air flow. This paper reports the effect of air flow on the behavior of free edge of a web.

The problem is similar to flag flutter since the edges of a paper web often have little tension and are usually slack. Thoma [1] tries to explain how a flag extracts energy from the air flow, based on an assumed flutter mode. A complicated mathematical analysis by Sparenberg [2] shows that the flutter frequency can be evaluated if we force the Kutta condition to be satisfied at the free edge. Another important point is that the drag of a fluttering flag is much higher than expected for a stationary flat plate [3]. A theoretical analysis [4] shows that the kinetic energy of an oscillating rope appears as an increase of tension due to the centrifugal force from the end whipping back and forth; the same theory holds for a fluttering flag or web.

The purposes of this study are to reveal the important features of edge flutter and to provide design guides. Since no exact analysis is available, we performed a dimensional analysis to find the important nondimensional parameters and then conducted wind tunnel tests. We proposed tentative stability criteria for edge flutter and suggested some ways of managing the air flows to minimize flutter damage.

NONDIMENSIONAL PARAMETERS

Nondimensional parameters are obtained either by Buckingham Pi Theorem or by nondimensionalizing the governing equation of the problem if the equation is known [5]. The following are the physical variables that might be important in the present problem and the nondimensional parameters derived from them:

Dependent	Variables	Dimension
U	Critical flow speed	LT^{-1}
ω	Flutter frequency	T^{-1}

Independent	Variables	Dimension
ρ	Air density	ML^{-3}
ν	Kinematic viscosity	L^2T^{-1}
a	Sound speed in air	LT^{-1}
d	Web width	L
L	Web length	L
m	Basis weight (areal density) of web	ML^{-2}
D	Bending stiffness of web (per unit width)	ML^2T^{-2}
T	Web tension in cross-flow direction (per unit width)	MT^{-2}

Nondimensional Parameters

$\frac{U}{\omega d}$	Reduced velocity
$\frac{Ud}{n}$	Reynolds number
$\frac{U}{a}$	Mach number
$\frac{L}{d}$	Slenderness ratio
$\frac{m}{\rho d}$	Mass ratio
$\frac{D}{Td^2}$	Stiffness parameter
$\frac{T}{md^2\omega^2}$	Tension parameter

The meaning and importance of these parameters are as follows:

(i) The first parameter - reduced velocity - is an important parameter for a variety of flow-induced vibration problems. It represents the ratio of flow speed to the speed of structural motion. For convenience, a variation of reduced velocity was defined as

$$\frac{q}{\rho d^2 \omega^2}$$

This new parameter, named the pressure parameter, would be used instead of the reduced velocity in analyzing the experimental data. This parameter, as well as the reduced velocity, contains a frequency term (ω). For most flow-induced vibration problems, vibration frequency can be predicted; that is not so for web flutter. This fact may limit the application of a stability criterion that contains ω.

(ii) The second one - the Reynolds number - is the ratio of fluid inertia to viscous force. It gives a measure of boundary layer thickness and transition from laminar to turbulent flow [6]. The Reynolds number is a crucial parameter in fluid dynamics problems, but in studying flow-induced vibrations, the effect of the Reynolds number is usually neglected [7, 8] and sometimes the requirement of the Reynolds number cannot be met in testing because of its incompatibility with the reduced velocity [9]. The effect of the Reynolds number was not considered in this study.

(iii) The Mach number is the ratio of flow speed to the sound speed; it is a measure of fluid compressibility and is important only when its value is high enough, say greater than 0.3. For the present study, the Mach number was low enough so that its effect was neglected.

(iv) The slenderness ratio determines the severity of three-dimensional behavior of web motion and the air flow.

(v) The mass ratio is very important in flow-induced vibration problems; the mass ratio is believed to be crucial in the edge flutter phenomenon.

(vi) The stiffness parameter defines the relative importance of bending rigidity and tension.

(vii) The last parameter - the tension parameter - contains a dependent variable, flutter frequency. The information of the critical flow speed is more important than the flutter frequency for practical purposes. Therefore, by combining it with the reduced velocity and mass ratio, the tension parameter can be changed to be

$$\frac{qd}{T}$$

The stability criterion might be expressed as a functional relationship of

$$f_1\left(\frac{q}{\rho d^2\omega^2}, \frac{qd}{T}\right) = f_2\left(\frac{m}{\rho d}, \frac{D}{Td^2}, \frac{L}{d}\right)$$

EXPERIMENTAL SETUP

The experimental model was a non-traveling web in a uniform air flow. The test web simulated one edge of the paper in a dryer section with lateral air flow; the downwind edge of the test web was free while the other sides were fixed (Fig. 1 and Fig. 2). We applied web tension in the cross-flow direction to simulate machine-directional tension in paper machines. For uniform tension distribution, the upwind edge area of the web had holes and parallel cuts, and the upwind clamp was released and fastened again whenever tension was changed. Paper webs were used in the first series of experiments, but it was very difficult to obtain uniform tension distribution. Later, we tested stretchable plastic materials which were easy to set up. We drew straight lines on the web, one-inch apart in both x and y directions, for better observation of web motions. We tried to measure web deflection using an optical sensor. The sensor had a rectangular rod shape with a cross section of 6 x 19 mm. After the first flow test, we gave up using the optical sensor because it affected web behavior as described in the next section. Instead, we used a stroboscope to reveal flutter pattern, frequency, and approximate values of amplitude. The operation range of the stroboscope is about 20 - 200 Hz.

Test variables were web material (basis weight, modulus of elasticity), web size, tension, and flow speed. Material properties and test conditions are summarized in Table 1.

RESULTS AND DISCUSSIONS

General Response Characteristics

As the flow speed was increased from zero, the free edge of the web started to vibrate randomly with small amplitudes. The amplitude grew with flow speed, and above a certain value of air speed (critical speed) the vibration became violent and steady as indicated in Fig. 3. We could determine the critical flow speed by measuring either vibration amplitude or frequency. In most cases, the transition occurred so suddenly that the critical flow speed could be determined with little uncertainty.

Once the web became unstable ($U > U_{crit}$), the flutter frequency usually increased with flow speed as shown in Fig. 4. The frequency of vortex-shedding from the web-holding jig was always much higher than the observed flutter frequency.

The free edge had the largest amplitude and the amplitude changed along the flow direction as shown in Fig. 5. Appreciable deflection occurred only in the area near the free edge.

The observed motion was traveling-wave type. In some cases where a portion of the web had much lower tension than the other areas, local flutter was observed in that area; again, the wave was traveling. With the stroboscope frequency a little lower than the flutter frequency, the wave appeared to move downstream; while with higher light frequency, the wave looked moving upstream. It simply means that the wave was always running downstream with the air flow.

The effect of reflected wave was not clearly observed. Usually, when a wave encounters a free (or fixed) boundary, the deflection (or stress) is doubled at the boundary and a standing wave appears. The wave observed near the fluttering free edge was much different from that. It seems that the kinetic energy of the free edge was not transferred from the upstream waves but induced by the local interaction between the free edge and the air, and the reflected wave running against the air flow was damped so heavily that its effect could not be observed.

Effects of Design Parameters

In most cases the critical speed of air flow was increased with web tension. The effect of web length, however, was not clear for the ranges of test variables. Web width was not changed during the tests. But the effect of web width could be deduced from the observations of cross-flow modes. Usually the cross-flow mode had zero-nodes (Fig. 6). But sometimes higher modes (more nodes and higher frequencies) appeared at higher flow speeds. The higher modes correspond to smaller web width; therefore wider webs might be more unstable than narrower ones. These results are reasonable because both web tension and web width affect the restoring force term but web length does not if it is much longer than the wavelength.

We could not separately test the effects of basis weight and bending rigidity because it was impossible to change one of them without affecting the other. The stability criterion - Equation (5) - shows that critical flow speed increases with both basis weight and bending rigidity.

Flutter frequency increased with web tension, but decreased with web length. Since no appreciable change of wavelength was found during the tests, the frequency change means change of wave speed. It should again be noted that the flutter frequency depends on flow speed and the web does not have its own characteristic frequencies.

When we mounted the optical sensor to measure web motion, the downwind edge deflected toward the sensor and fluttered severely in the whole range of flow speed. Any flow obstructions that cause unbalance in static pressure on the two sides of the web would make the web more vulnerable to flutter.

Stability Criteria

As already described, the effect of slenderness ratio was not certain, so its effect was not considered in developing the stability criteria. Therefore, the stability criteria might be expressed by either one of the following two forms:

$$\frac{q}{\rho d^2 \omega^2} = f\left(\frac{m}{\rho d}, \frac{D}{Td^2}\right) \qquad (1)$$

or

$$\frac{qd}{T} = f\left(\frac{m}{\rho d}, \frac{D}{Td^2}\right) \qquad (2)$$

At first, the correlation among three parameters of the following form was determined.

$$\left(\frac{q}{\rho d^2\omega^2}\right) = A\left(\frac{m}{\rho d}\right)^a \left(\frac{D}{Td^2}\right)^b + B \qquad (3)$$

where A, B, a, and b are unknown constants. These four constants were determined as follows:

(i) Set values of the powers, a and b.

(ii) Obtain an x-y chart of the two groups of experimental data, one group for paper webs and the other for plastics, where

$$x = \left(\frac{m}{\rho d}\right)^a \left(\frac{D}{Td^2}\right)^b \quad \text{and} \quad y = \frac{q}{\rho d^2\omega^2}$$

(iii) Determine the best-fit linear curve for each group of data.

(iv) Change the values of a and b to find ranges of them that make the two curves overlap or come close.

(v) Change a and b within these ranges and find the best-fit linear curve and corresponding correlation coefficient for the whole data set. Repeat it until the largest value of correlation coefficient is found.

After many trials, the correlation equation was obtained as (Fig. 7)

$$\frac{q}{\rho d^2\omega^2} = 4.78 \left(\frac{m}{\rho d}\right)^{1.2} \left(\frac{D}{Td^2}\right)^{0.5} + 0.00185 \qquad (4)$$

The corresponding correlation coefficient is $r = 0.88$.

The stability criterion of the second form, determined by the same method as for the first one, is

$$\frac{qd}{T} = 779 \left(\frac{m}{\rho d}\right)^{0.5} \left(\frac{D}{Td^2}\right)^{0.7} + 0.200 \qquad (5)$$

with a correlation coefficient of $r = 0.85$ (Fig. 8).

CONCLUSIONS AND APPLICATIONS

We tested edge flutter in a wind tunnel using stationary (non-traveling) webs. The free edge of a web started to vibrate at a critical flow speed and its amplitude grew drastically with flow speed. The actual environments of paper webs in a paper machine are much different from our simplified test model. It seems safe, however, to conclude that the air flow, without any other suspected causes, can induce detrimental edge flutter in paper machines. Proper control of the air flow is essential to prevent flutter damage.

The local interaction of the free edge with the air flow is critical. We can reduce flutter damage by minimizing flow speed near the free edges. An example of one possible solution is shown in Fig. 9. Design (b) reduces outflow at the edge by supplying more drying air at the center but less air volume overall. Design (b) is better than (a) as far as the edge flutter is concerned because there is less air velocity at the edge, yet effective drying in the crucial central area is just as good.

Another way to minimize the air flow near the free edges is to use a ventilation system that has both air supply and vacuum sections so that the air flows in the machine direction with no net outflow or inflow at the edges (Fig. 10).

Equation (4) or (5) can be used as a rough guide for predicting edge flutter. Equation (4) requires frequency information that may not be available. Equation (5) is more straightforward to apply. We should be aware of the limitations of the stability equations. Especially, the effect of machine-directional web dimension might be very important but is not included in the equations. Further study is needed to verify the effect of web size.

Equation (5) shows how each design parameter contributes in edge flutter and gives a direction for preventing edge flutter. We can prevent the edge flutter by increasing web tension, bending rigidity, and basis weight. Cedercreutz [10] suggests that flutter damage could be prevented by making the edges thicker than the other areas. That method would work because we can increase the bending rigidity and basis weight by increasing the thickness of a web.

Another possible cause of flutter is the unequal flow speeds (or pressures) on the two sides of the web [10, 11]. As observed in this study, an obstruction near the free edge might substantially reduce the critical flow speed. Ventilation systems that are not properly designed may cause static web deflection and edge flutter.

This study was limited to stationary webs; continuing experiments are needed to verify the effect of web motion on stability.

ACKNOWLEDGMENTS

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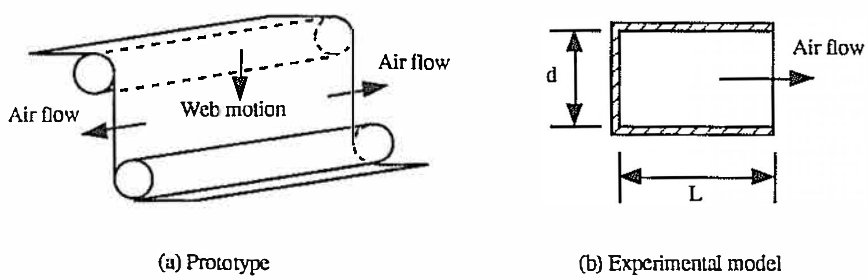

Fig. 1 Experimental modeling of edge flutter

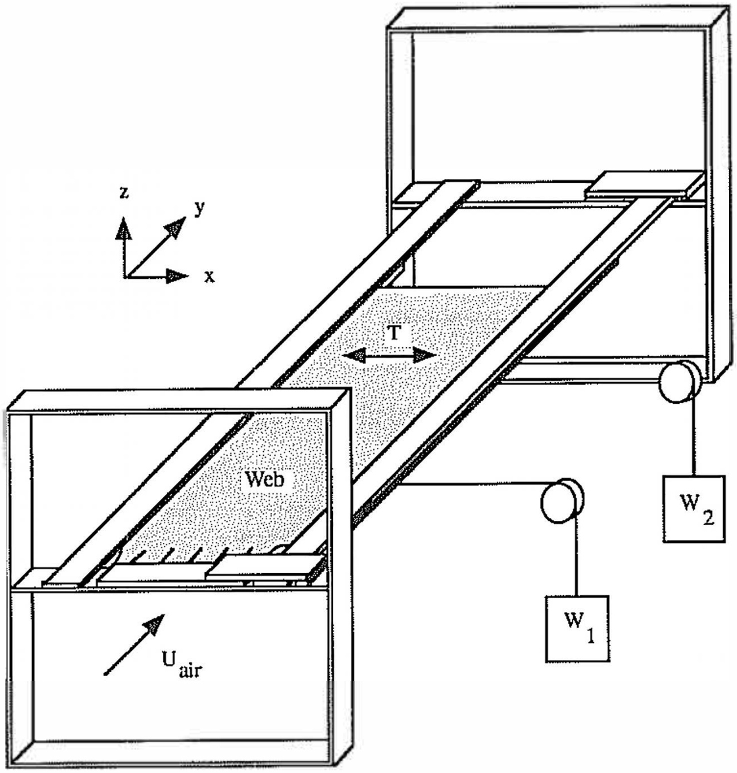

Fig. 2 Setup for edge flutter tests

Table 1 Material properties and test conditions

	Paper	Plastic 1	Plastic 2	Plastic 3
m (Kg/m^2)	0.058	0.023	0.12	0.24
E (Pa)	6.8×10^9	5.0×10^7	5.0×10^7	5.0×10^7
d (m)	0.23	0.23	0.23	0.23
L (m)	0.30, 0.38, 0.46	0.46	0.46	0.46
T (N/m)	9 - 70	35 - 70	18 - 70	9 - 70

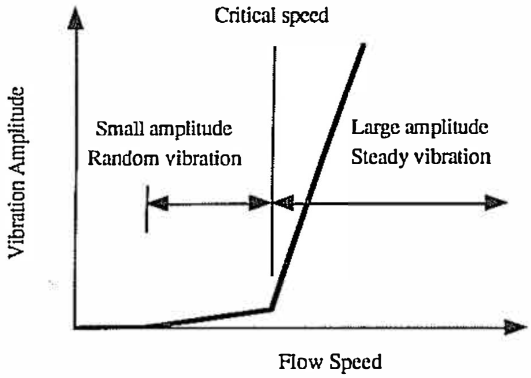

Fig. 3 Typical amplitude response characteristics of edge flutter

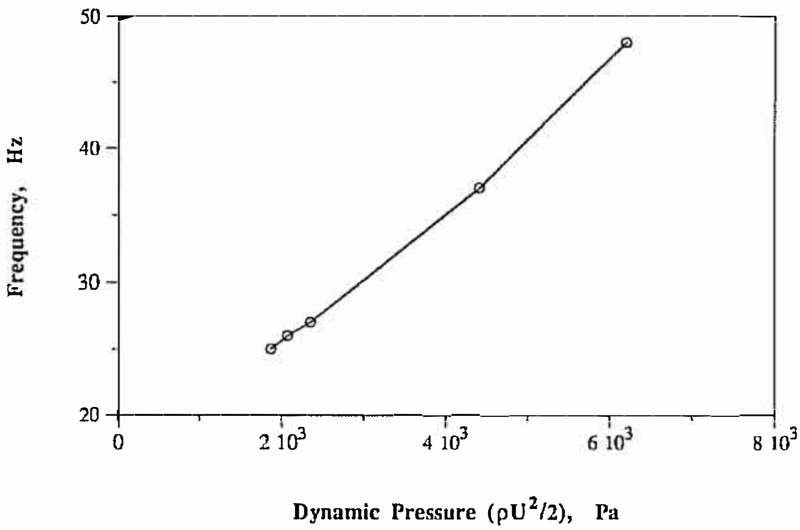

Fig. 4 Frequency response of a paper web (0.24 x 0.48 m, 17 N/m)

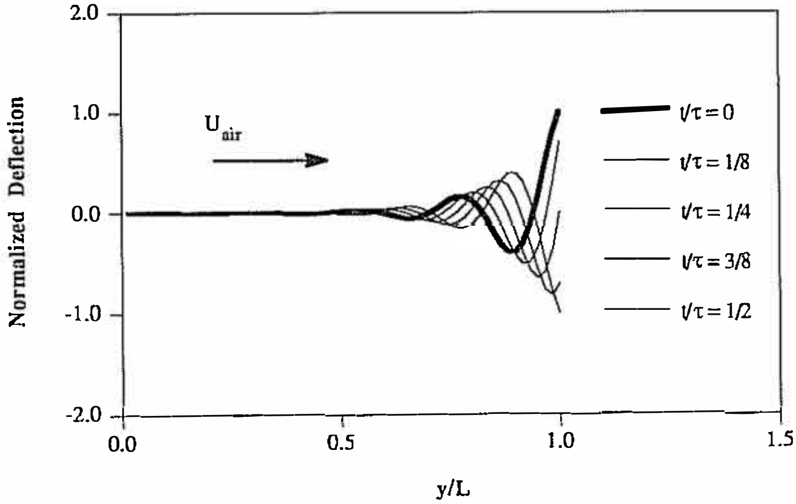

Fig. 5 Pattern of edge flutter (First half cycle)

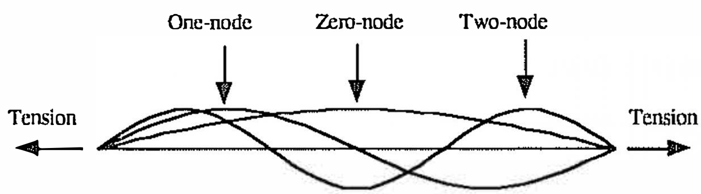

Fig. 6 Cross-flow modes (Upstream view of free edge)

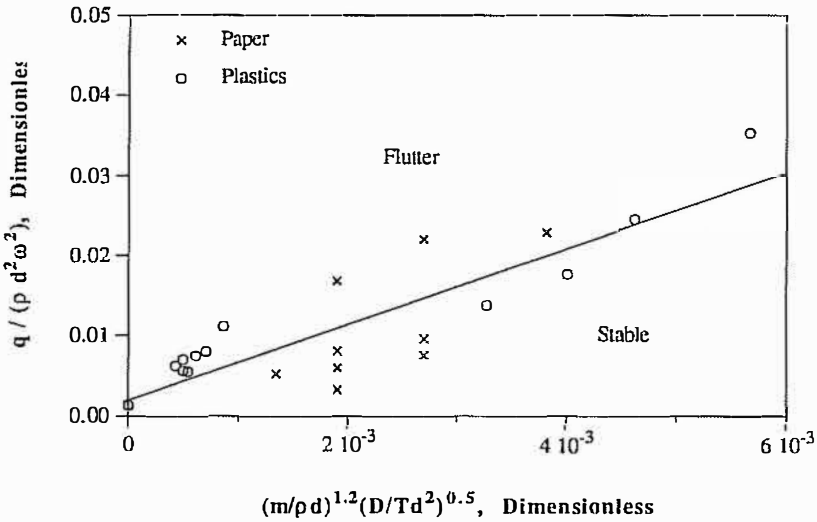

Fig. 7 A tentative stability criterion (Type 1)

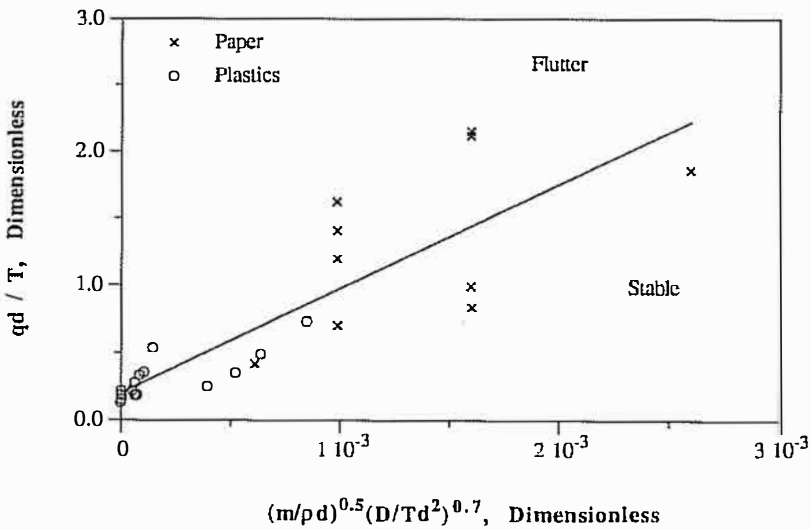

Fig. 8 A tentative stability criterion (Type 2)

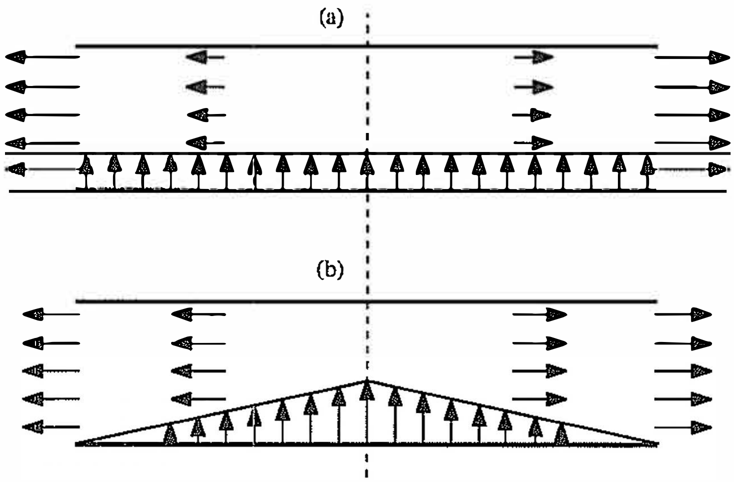

Fig. 9 Design of ventilation air supply distribution

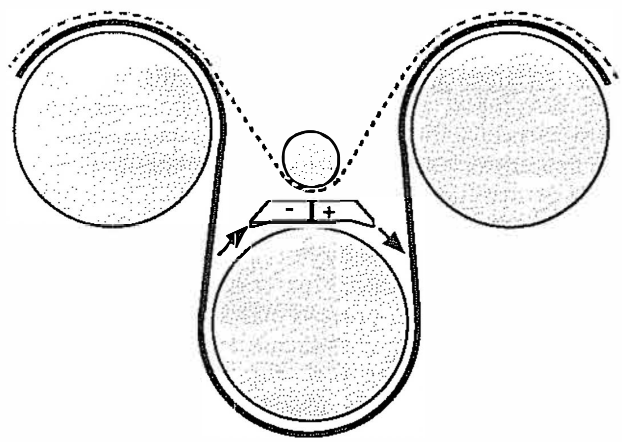

Fig. 10 Design of balanced blow and suction boxes