WEB FLUTTER AT CIRCULAR-TUBE AIR-TURN BARS

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ABSTRACT

Circular tubes having air-emitting holes are often used for non-contact handling of photographic and magnetic media and for printed paper webs. One of the problems of circular-tube air-turn bars is their tendency to cause flutter, sometimes accompanied by a buzzing sound. An experimental study of such a flutter problem is discussed in this paper. Vibration of a web supported by air-turn bars was measured for different values of supply pressure of air, web tension, and wrap angle. It is shown that different types of flutter can occur at different operating conditions. This study resulted in parameter maps which show the regions of operating conditions for different types of flutter.

NOMENCLATURE

C	Coefficient of discharge
d	Diameter of air-emitting holes on air-turn bar
N	Total number of holes on air-turn bar
N_{CD}	Number of air-emitting holes in each row
N_{MD}	Number of rows on air-turn bar
P_a	Ambient pressure
P_o	Air pressure inside air-turn bar
Q	Mass flow rate
R	Outside radius of air-turn bar
R_{tot}	Flow resistance of air-turn bar, $R_{tot} = (P_o - P_a)/Q_{out}^2$ without web
S_{CD}	Cross-directional pitch of air-emitting holes
S_{MD}	Machine-directional pitch of air-emitting holes
T	Web tension (force per unit width)
W	Web width

α	Angle covered by air-emitting holes
γ	Overwrap angle (Fig. 2); when positive, all holes are covered by web
ρ	Mass per unit volume of air

INTRODUCTION

A variety of air-turn devices (also called airturns) are widely used for changing the direction of a moving web without contact. Many modern air-turn devices consist of five or more pressure-pad air bars arranged in a circular pattern. Designs and applications of these air-turn devices are explained in [1 and 2]. A simpler way of design is to use two opposing air jets as described in [3 - 7]. These two types of air-turn devices utilize the principle of ground effect discussed in [8 - 11]. Another way to construct an air-turn device is to use a circular tube (or a part of it) with air-emitting slots or holes [12]. It is also possible to use a porous material for the tube [13]. Tubes with air-emitting holes can be used not only for non-contact supporting of webs, but also for drying of coated films [14] and for removing wrinkling in a moving web [15]. Some of the important characteristics and applications of tubular air-turn devices are discussed in [16].

One of the annoying problems in air-turn devices is web vibration. For the first two types of air-turn devices, violent web flutter can occur when the flotation height (distance between the web and the air-turn devices) becomes small due to excessive web tension, with supply pressure still high enough to support the web. The same kind of flutter problem is observed at air bars back in air flotation ovens. For circular-tube air-turn devices, at least two peculiar phenomena are observed in industry. One of them is a large amplitude bumping motion of the web: the web is floated with increasing height up to a certain limit and then it drops toward the air-turn bar. This cycle repeats at a constant frequency and the web bumps the air-turn bar repeatedly, resulting in tension fluctuation in the free span of web adjacent to the air-turn bar. Tension fluctuation, in turn, can cause serious vibration problems in the free span. Another phenomenon is violent, high-frequency flutter of the web near the tangents (locations where the web approaches and leaves the air-turn bar) which can be accompanied by a loud buzzing sound. This paper discusses such dynamic web instability problems at air-turn bars made of circular tubes. The term "air-turn bars" will be used throughout this paper to indicate exclusively those air-turn devices made of circular tubes. Our prime objectives for this study are to identify all possible types of web vibration phenomena at air-turn bars, to understand the underlying physics of air-web interaction at air-turn bars, and to provide information needed for design improvements.

EXPERIMENTS

Web Instability at Air-Turn Bars

Test Setup. The setup for web instability experiments consisted of an air supply, a circular tube *60 mm* in outside diameter, and a web *152.4 mm* in width, as shown in Figs. 1 through 4. Since the web was narrow, it was necessary to use air dams to prevent side leakage of air. The air dams were mounted as close to the web as possible without hindering the out-of-plane motion of the web. The maximum air gap between the web and air dams was approximately *0.5 mm*. In order to simplify the experiments, one end of the web was fixed on the air-turn bar. The tested web material is a $0.055\ mm$-thick plastic film with a mass per unit area of $0.071\ kg/m^2$. Web tension was adjusted by changing the weight attached to the web through a flexible rubber hose with a spring constant of $K \approx 100\ N/m$.

Air sources. Two different air sources–an air compressor and a blower–were used. When we use compressed air, the air flow rate can be well controlled regardless of pressure fluctuation inside the air-turn bar. On the other hand, a blower can deliver nearly uniform outlet pressure even when the flow rate varies within a certain range. In order to quantitatively evaluate these characteristics of air sources, the relationship between the flow rate and the pressure load (air pressure inside the air-turn bar) was determined as follows. The pressure regulator of compressed air was set at a given value and the inside pressure of an air-turn bar was measured for various number of open holes. This test was repeated for different air-turn bars having different hole diameters ($d = 1.6$ and $3.2\ mm$). The flow rate was calculated from the equation for liquid discharge from an opening made of a short pipe [17],

$$Q_{\text{discharge}} = \rho\left(C_v\sqrt{\frac{2\Delta P}{\rho}}\right)\left(C_c\frac{\pi d^2}{4}\right) \tag{1}$$

where C_v is the coefficient of velocity, C_c is the coefficient of contraction, and $C = C_v C_c$ is the coefficient of discharge known to be

$$C = 0.8 \tag{2}$$

Since the tube wall thickness is $4.2\ mm$, and the length of flow path (wall thickness) to diameter ratios are 1.3 and 2.6, it is believed that the short-pipe assumption is valid for our test setup. Note that Eqs. (1) and (2) are for the case where liquid discharges into air, and in our problem air discharges into air. It is known, however, that this difference does not affect the coefficient of discharge for orifice discharge [18]. The mass flow rate of air is obtained as a function of pressure regular setting as shown in Fig. 5. It is seen that the mass flow rate is linearly proportional to the regulator setting and their relationship is obtained as $Q = 0.0004414 + 1.817x10^{-8}P_{regulator}$, where the flow rate is in kg/s and the regulator pressure setting is in N/m^2. Figure 6 shows that for given regulator setting, the mass flow rate is nearly constant regardless of the pressure inside the air-turn bar.

Air-Turn Bars. Several air-turn bars were tested to study the effects of the diameter and pattern of air-emitting holes. An air-turn bar can be characterized by the diameter and pattern of air-emitting holes and the outside radius of the tube. In this study, the radius of the air-turn bars is fixed at $R = 30\ mm$. Three different types of hole arrangements were tested: in-line array, staggered array, and single row of holes. One of the factors which may represent the characteristics of an air-turn bar is to define the total flow resistance, which can be defined as

$$R_{tot} = \frac{P_o - P_a}{Q_{out}^2} \quad \left(\frac{1}{N \cdot s^2}\right) \tag{3}$$

Using Eqs. (1), Eq. (3) can be rewritten as

$$R_{tot} = \frac{8}{\rho\left(NC\pi d^2\right)^2} \tag{4}$$

Some of the characteristics of the air-turn bars with the in-line hole arrangements are summarized in Table 1.

Procedure. The main test variables include the supply flow rate or supply pressure, web tension, type of air-turn bar (diameter and arrangement of air-emitting holes), and the overwrap angle γ defined in Fig. 2. This angle defines the location of tangent (location where the web meets the air-turn bar) compared to the location of the outermost row of air-emitting holes; when it is positive, all holes are covered by web. For each air-turn bar, the pressure regulator reading is adjusted to yield a desired mass flow rate, the web tension is set at a desired value, and then the overwrap angle is adjusted while the behavior of the web is observed. When the web flutters, the major frequency components are measured using a laser-Doppler vibrometer and a spectrum analyzer.

Results. It is found that when the angle γ is large and negative, that is, when there is an excessive amount of air leakage, the web cannot float but touch the air-turn bar. The same situation occurs when the web tension is excessive compared to the capacity of air supply. The requirement of the air pressure in the air-turn bar can be expressed as

$$P_o - P_a \geq \frac{T}{R} \tag{5}$$

When the supply pressure does not satisfy the above requirement, the web cannot float at all. The required magnitude of the air pressure inside the air-turn bar depends on the flow resistance of the bar. On the other hand, the flow rate should be sufficient to keep the required pressure inside the bar if there is any leakage flow.

For air-turn bar A, which has the largest flow resistance, it is found that the flow resistance is too excessive. When the pressure regulator of the compressed air is set at $6.89x10^4\,N/m^2(20\,psi)$ or when the mass flow rate is approximately $0.0030\ kg/s$, the pressure inside the air-turn bar is measured to be approximately $3.8x10^4\,N/m^2\ (5.5\,psi)$. At that condition, the web is floated freely when $T/R < 2100\ N/m^2(0.30\,psi)$ and $\gamma > -50^o$. For higher values of web tension, the angle γ needs to be nearly zero or positive for stable flotation.

For air-turn bar B, there are regions of operating conditions where the web flutters violently. The lines in Fig. 7 are shown blurry because the web vibrates with a large amplitude. The portion of web which covers the air-turn bar oscillates up and down and the free span experiences a normal mode out-of-plane vibration. It appears that the vibration of the free span is caused by tension fluctuation which in turn is caused by the bumping motion of the web. Figure 8 is the stability map for the mass flow rate of $0.0030\ kg/s$. It is noticed that there are four regions: a region where the web does not float, a region where the web floats stable, a region where violent flutter occurs, and a region where the web vibrates with a weak buzzing noise. This last region is not clearly distinguished. The region where the web does not float indicates that too much air leaks through the holes outside the covered area and the web tension is high. Note that web flutter occurs only when the angle γ is nearly zero, or when the outermost row of air-emitting holes is located near the tangent. Figures 9 and 10 are for increased mass flow rates. When the mass flow rate is doubled (Fig. 10), it appears that the region of stable operation becomes very wide. It was discovered during the experiments that the alignment of the air-turn bar and the web is very critical. When there is any misalignment which causes nonuniform web tension, the loose side of web tends to buzz and bumping vibration tends to disappear. Therefore, if high frequency noise is the dominant problem and if it occurs at a portion of the width of web, the problem can be related with nonuniformity of web tension.

The diameter of the air-emitting holes on air-turn bar C is bigger than that for air-turn bar B. Its flow resistance, however, is much greater than bar B because the number of holes on bar C is so small. In general, the performance of air-turn bar C is similar to that of bar A which has a large flow resistance. No particular web instability phenomenon were observed from air-turn bar C.

For air-turn bar D, which has the lowest flow resistance, the stability maps are shown in Figs. 11 through 13. The general trend is similar to that for air-turn bar B. Note that bar D is similar to bar B rather than C when we consider their flow resistance. It seems that the hole arrangement is less important than the overall flow resistance. One thing which makes the bar D different from the bar B is that very strong buzzing noise can occur at bar D.

The effect of the volume of air-turn bars was examined. For air-turn bar B, the air volume is $4.4x10^{-4} m^3$ including the volume of the connecting hose. When the mass flow rate is $0.0030\ kg/s$, the main flutter frequencies were 20.5 Hz and 41.0 Hz. When the volume was increased to $7.9x10^{-4} m^3$ by attaching an additional tube, the main frequencies became 15.5 Hz and 31.0 Hz. It is clearly seen that the total volume of air-turn bar and air duct affects web instability at air-turn bars.

Diverging Channel Flutter Experiments

Test Setup. The effects of air flow at the diverging area at air-turn bars are studied. In order to control the air gap between the web and the channel surface (equivalent to the air-turn bar surface), a test setup was constructed as shown in Fig. 14. The web material used for this test is the same as for the experiments explained before. The web width is $152.4\ mm$ for all cases. The main test variables include the air gap between the web and the opposing rigid wall, flow rate (or flow velocity at the nozzle), and web tension.

Results. It is observed that the air flow from the nozzle always follows the web surface and not the surface of the curved wall. When the flow velocity is low, the web is nearly stationary and there is no buzzing sound. At high flow velocities, however, the web is deflected toward the opposing curved wall and vibrates violently. This vibration results in a noisy buzzing sound which is nearly identical to what occurred during the air-turn bar experiments. The vibration amplitude (RMS velocity amplitude) changes as a function of the flow velocity at the gap as shown in Fig. 15. A stability criterion is obtained as shown in Fig. 16 by repeating the test for various values of the air gap at the nozzle.

DISCUSSION

The bumping instability which causes tension fluctuation and violent vibration in the free span appears to be controlled mainly by three factors: the support pressure between the web and the air-turn bar (T/R), the flow rate of air, and the wrap condition (γ). This phenomenon occurs when the support pressure is high, the flow rate is low, and outermost row of holes is near the tangents (or γ is not much different from zero). In practice, the angle γ needs to be nearly zero except for the air-turn bars with holes all around the tube. Bumping occurs at a dominant frequency and its harmonics and subharmonics, and the dominant frequency depends on the design and operating conditions of both the air-turn bar and the web. When the air volume in the air-turn bar is increased, the dominant frequency tends to be reduced.

CLOSING REMARKS

In order to avoid the bumping flutter at air-turn bars, it is necessary to limit the required support pressure, which is the web tension divided by the outer radius of the bar, below a certain limit. Based on our experiments, bumping instability may not be a problem if the required support pressure, T/R, is below $800\ N/m^2\ (3\ in-H_2O)$.

In order to avoid high-pitch noise and vibration in the web near the air-turn bar, the flow rate must be restricted and/or the geometry of the air-turn bar adjusted near the tangents. The key is to prevent excessive negative pressure near the tangents due to the Bernoulli effect. Also, when tension distribution is nonuniform, the slack edge of the web near the tangents can vibrate at high frequency and radiate a buzzing sound.

ACKNOWLEDGMENTS

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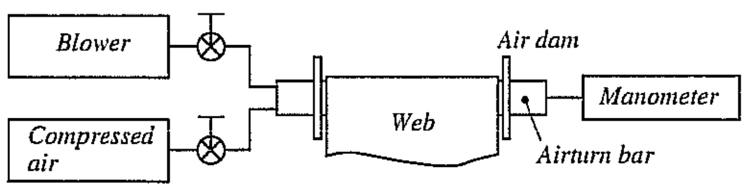

Figure 1. Schematic of the experimental setup

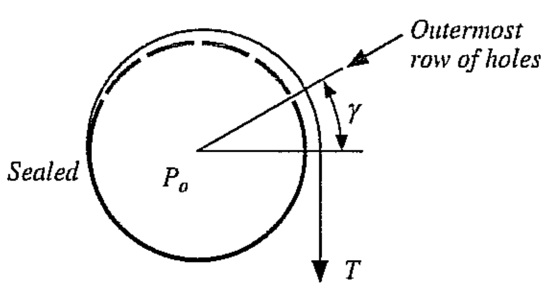

Figure 2. Cross sectional view of air-turn bar and mounting of web

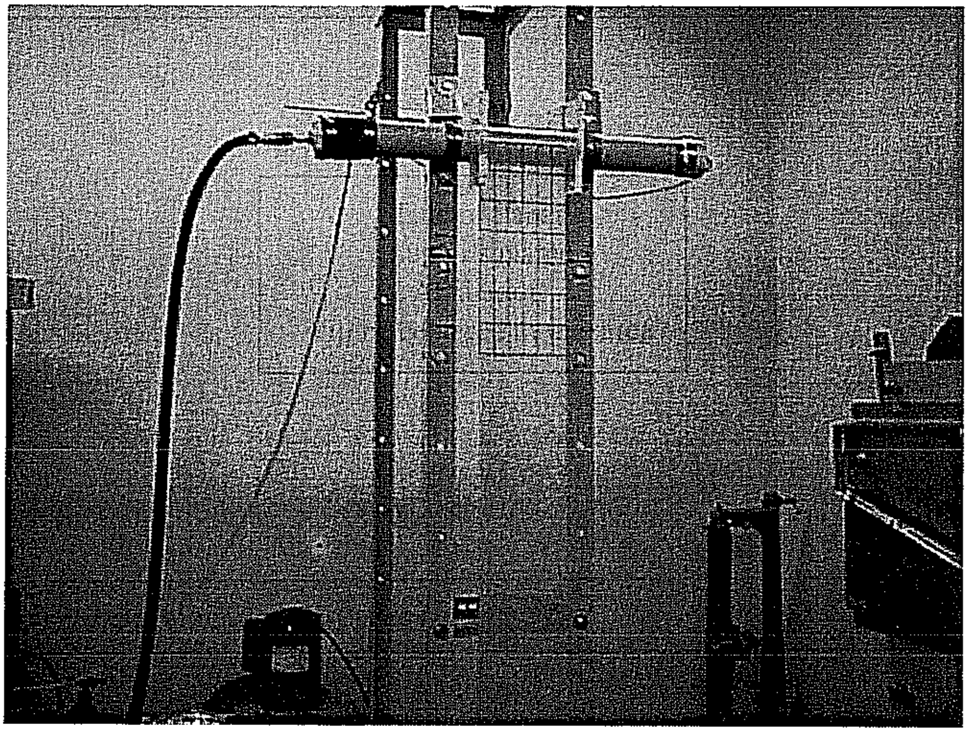
Figure. 3 Test setup

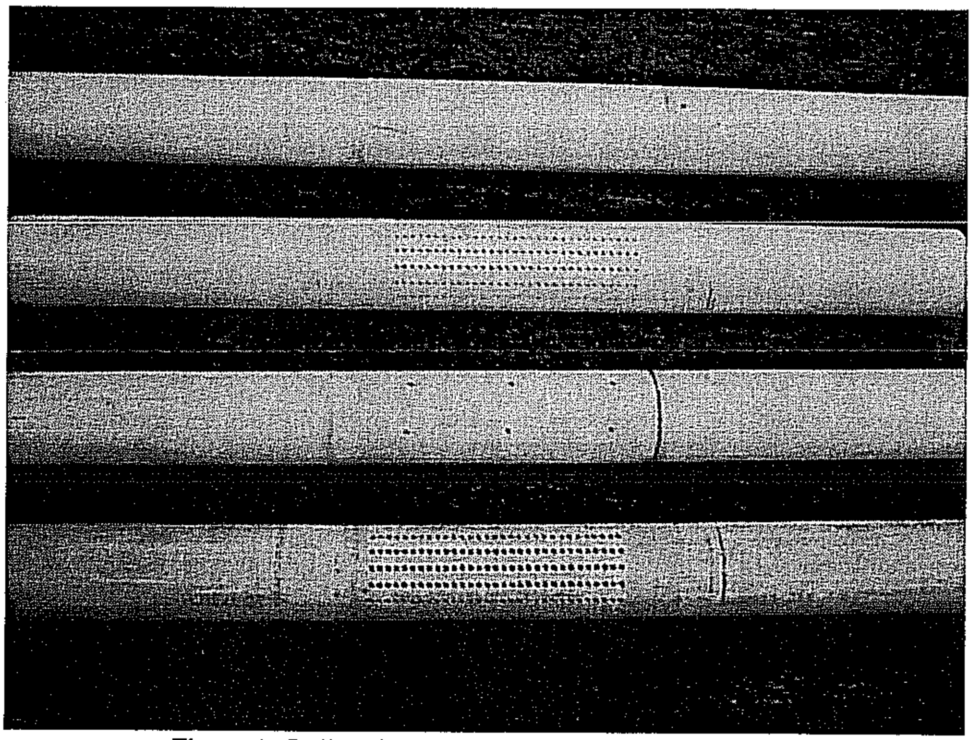
Figure 4. In-line air-turn bars (from top to bottom: A, B, C, & D)

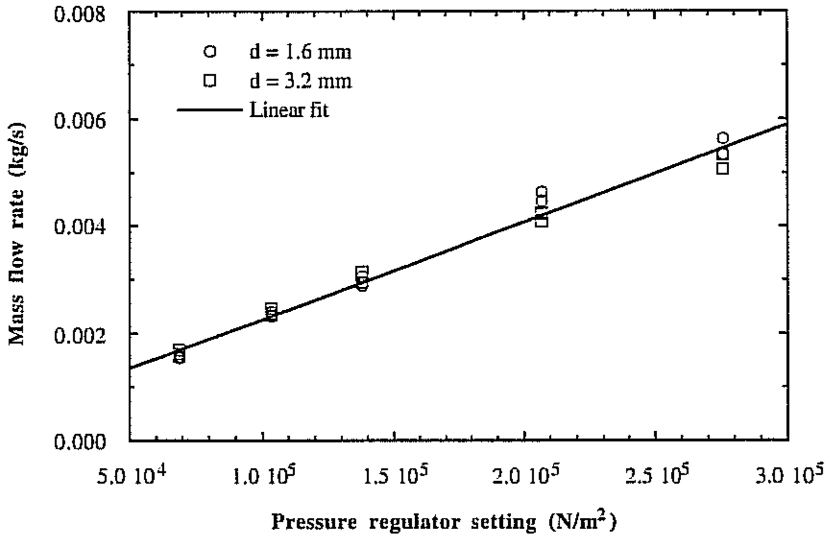

Figure 5. Calibration of pressure regulator

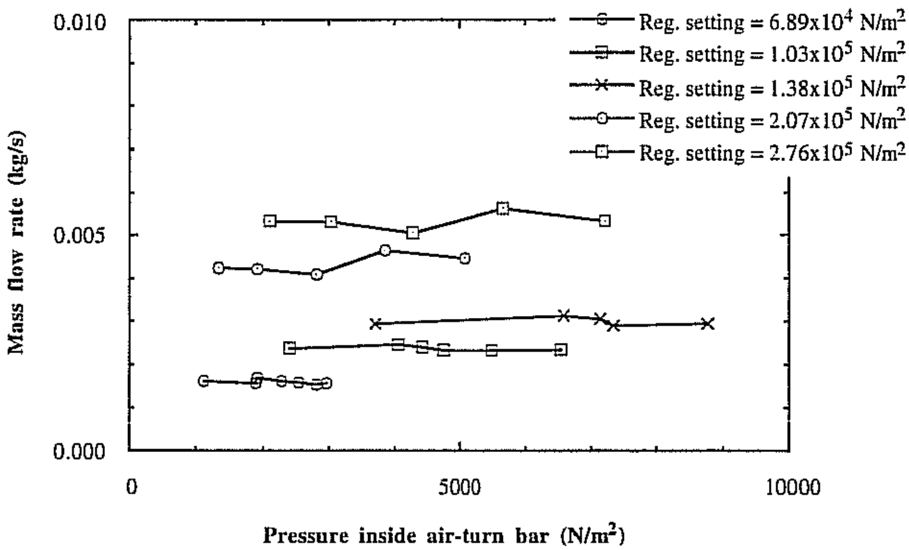

Figure 6. Characteristics of air compressor

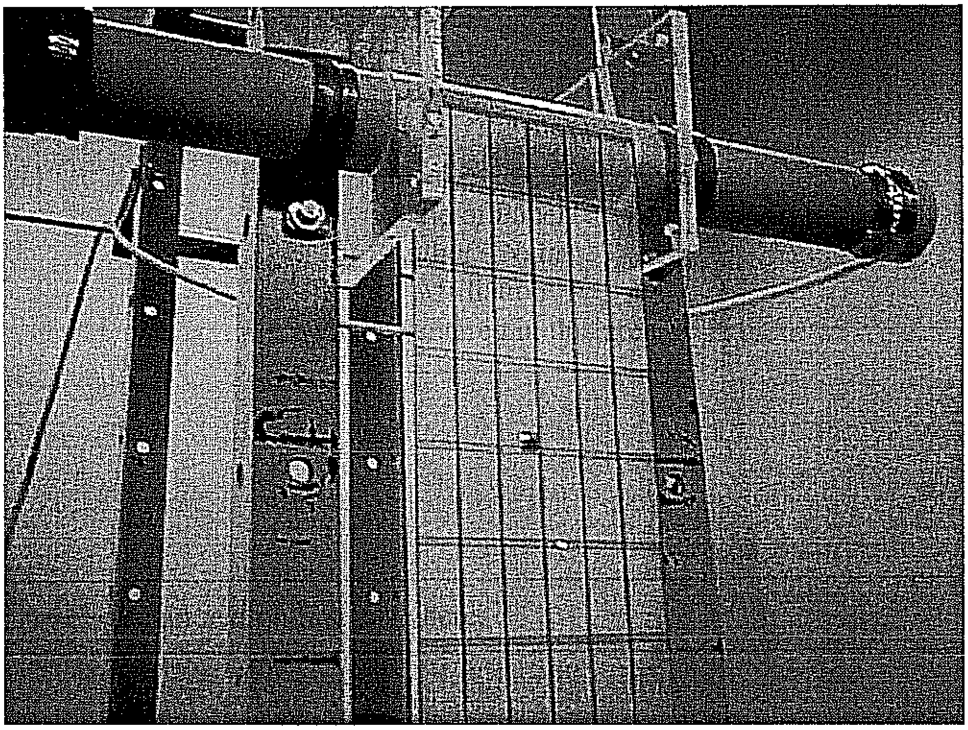

Figure 7. Bumping instability and free span flutter

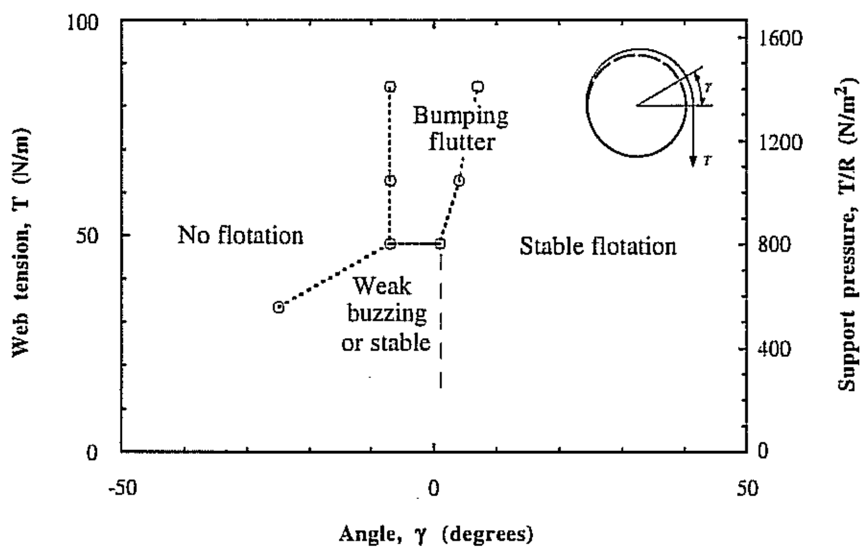

Figure 8. Stability map (Bar B, d = 1.6 mm, Q = 0.0030 kg/s)

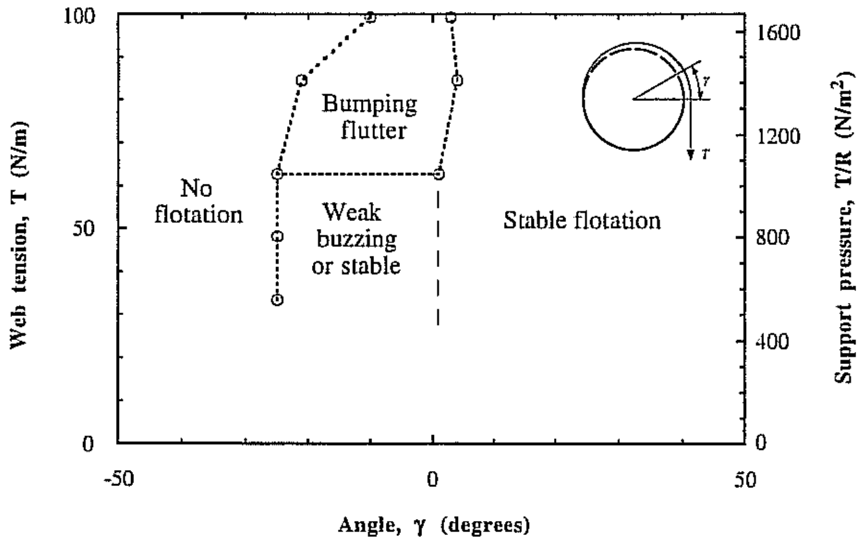

Figure 9. Stability map (Bar B, d = 1.6 mm, Q = 0.0045 kg/s)

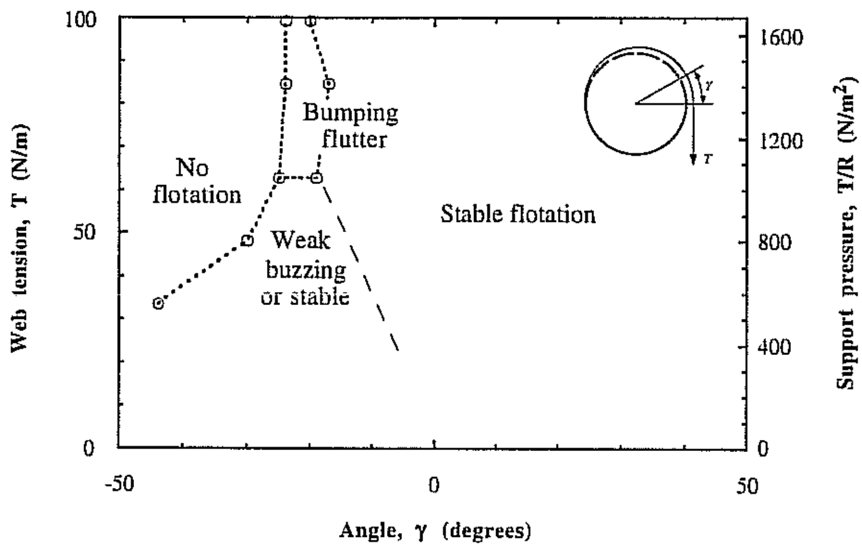

Figure 10. Stability map (Bar B, d = 1.6 mm, Q = 0.0060 kg/s)

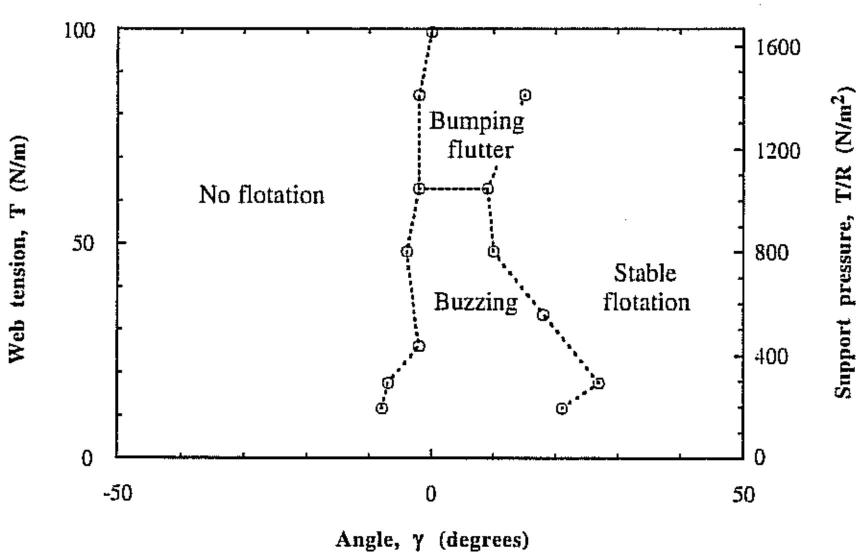

Figure 11. Stability map (Bar D, d = 3.2 mm, Q = 0.0030 kg/s)

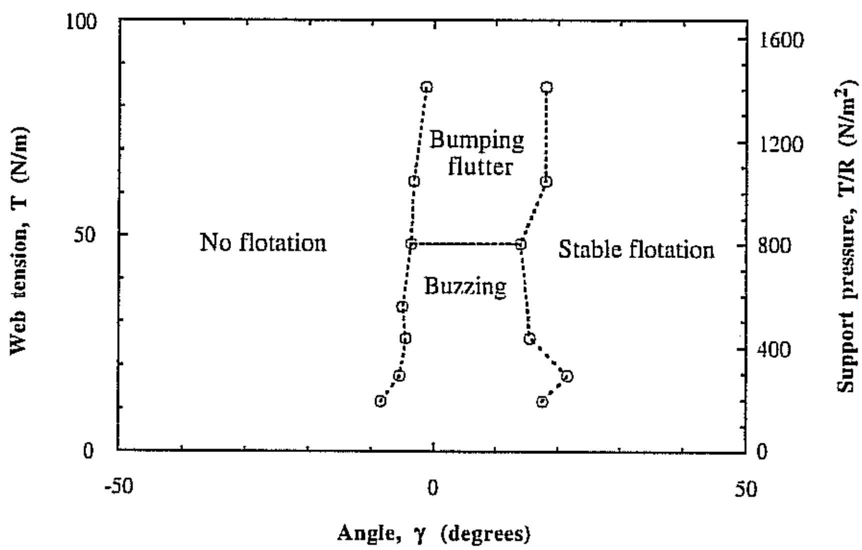

Figure 12. Stability map (Bar D, d = 3.2 mm, Q = 0.0045 kg/s)

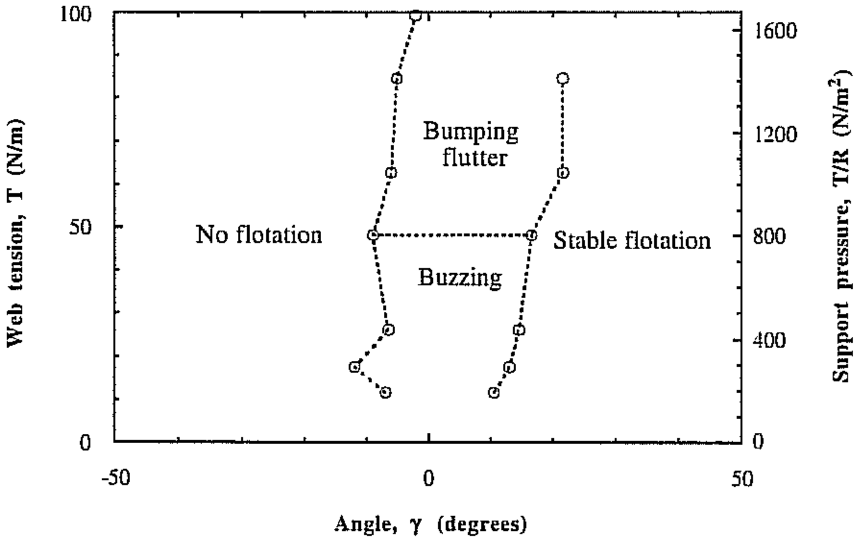

Figure 13. Stability map (Bar D, d = 3.2 mm, Q = 0.0060 kg/s)

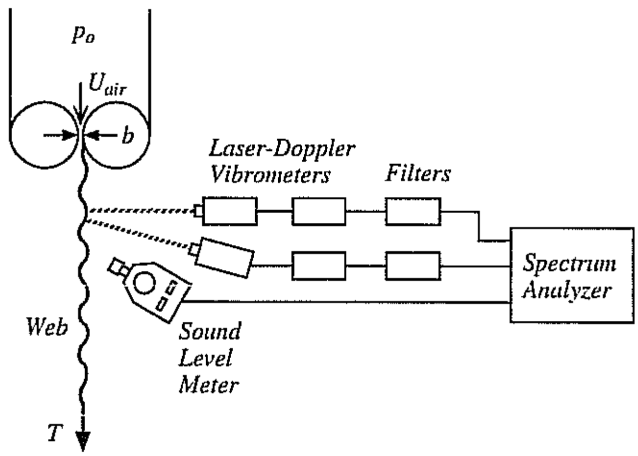

Figure 14. Test setup for diverging channel flutter experiments

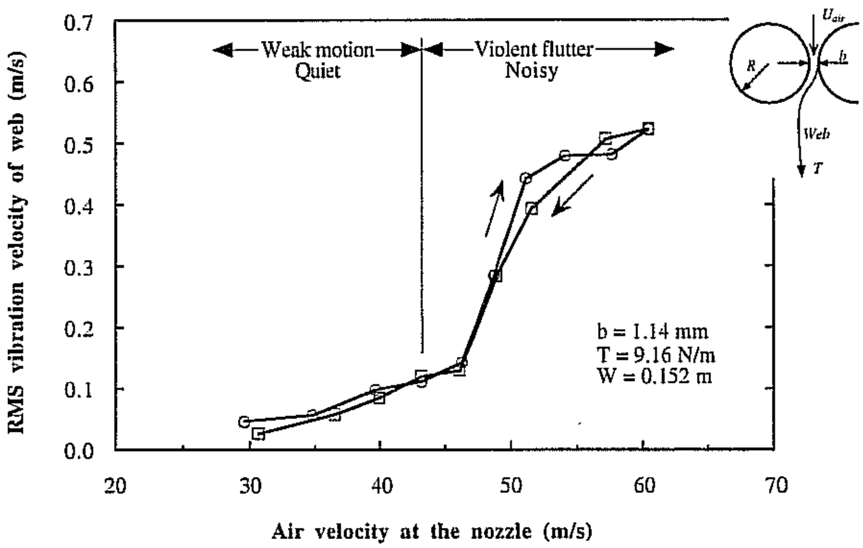

Figure 15. Effect of air flow on web vibration

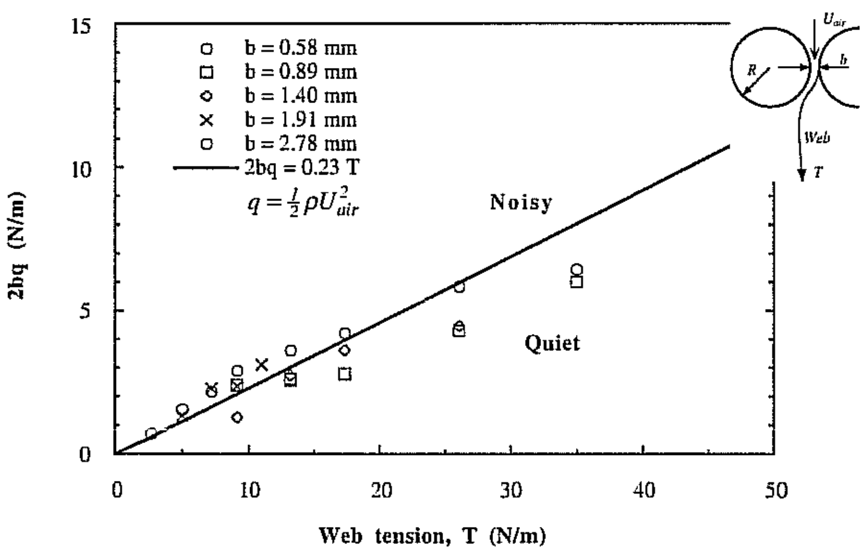

Figure 16. Buzzing criterion

Table 1. Characteristics of the tested in-line air-turn bars

Bar ID	$R(mm)$	$d(mm)$	$S_{MD}(mm)$	$S_{CD}(mm)$	N_{MD}	N_{CD}	$\alpha(deg)$	$R_{Tot}(1/N \cdot s^2)$
A	30	0.8	15.7	50.8	7	4	180	3.40×10^9
B	30	1.6	10.5	5.1	8	31	140	2.71×10^6
C	30	3.2	31.4	63.5	3	3	120	1.28×10^8
D	30	3.2	10.5	5.1	8	31	140	1.69×10^5

Question - Your tests were with a wrap angle of 180 degrees. The size of the bearing pad relative to the leakage parameter was high. If the wrap angle is close to 45 or 50 degrees, you have a less efficient air pad. For such a small wrap angle, would these results still apply?

Answer - We got rid of side leakage by using two air dams so that the wrap angle did not affect side leakage at all. We did study the effect of air leakage through the holes outside the area covered by the web, which appeared to be very important. When the wrap angle is small and most of the air escapes through uncovered holes, the web tends to touch the air-turn bar at high web tension.

Question - You had air dams on two sides and sealed the web at one end, forcing all air to flow in one direction through the wrap and creating a worse situation compared to the real operating situation. Your instability criteria would be different if you had a half of the air flow each way.

Answer - Actually not, because the flow velocity in the gap is mainly affected by the cushion pressure, which is the tension divided by the radius of the tube. Our test results show that the flow velocity, not the flow rate, is important within the range of our test conditions.

Question - Did you study the influence of the nozzle shape or the shape of each hole?

Answer - No. Each air-turn bar we tested has circular holes. We are interested in realistic designs which can be manufactured easily and at low cost.

Question - You used a weight to apply web tension. When the weight vibrates the web tension should be affected. Did you always use a mass and spring?

Answer - We used a very soft spring to attach the weight to the web. Even when the web fluttered violently, the weight did not move up and down. Therefore, the web tension was nearly constant while the web was vibrating.

Question - When you look at web stability in a static state opposed to a running state, you get different results. You may need to study the effect of a running web.

Answer - We did not want to start with a complicated model. We tried to minimize the factors in our study. I agree that the effect of web velocity is important, and it will be included in a future study.

Question - A traveling string vibrates differently than a stationary string. That dynamic effect needs to be included.