SUPPRESSION OF WEB FLUTTER BY

CHANGES IN FLOW PATTERNS

By

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CHAPTER 1

INTRODUCTION

Overview of the problem

Webs are materials that are manufactured and processed in a continuous-strip form. Web materials include extremely thin plastics, paper, textiles, metals, and composites.

Improvements in the paper making technology made it possible the design of paper machines operating at the speeds in excess of 3000 fpm [1]. However, many

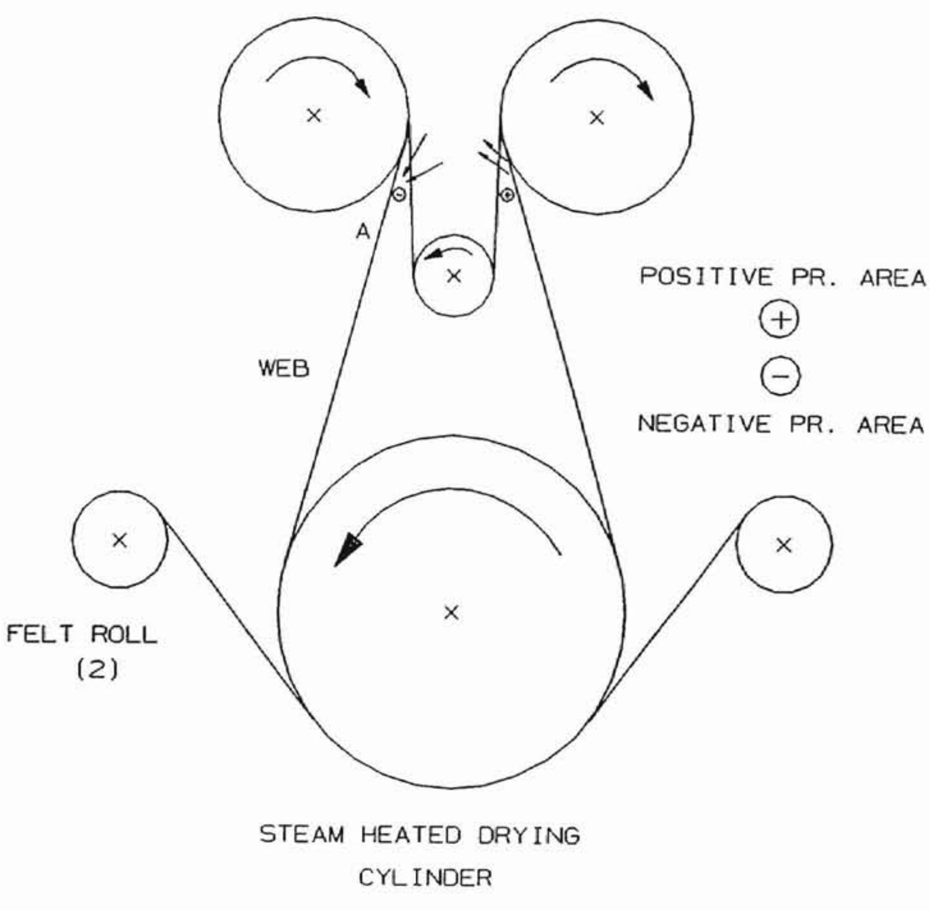

Fig. 1. Typical Dryer Pocket.

paper machines have been operating below their operating capacity (generally 10 to 20% below design speed), because of the problem of web flutter. Web flutter is a serious and a complex problem. It can lead to breaks in paper machines, to register errors in the printing presses, and to damage to the coatings on polymer sheets.

The problem of web flutter can occur in a conventional press and dryer section of a paper machine. A schematic representation of air movement in a drier pocket is shown in Figure 1. The dryer fabric and the web approaching the pocket carry on their upper side layers of air. Also, at the ingoing nip and the outgoing nip, negative and positive pressure region are formed which induces air to flow through the fabrics. Furthermore, due to forced pocket ventilation, air flow takes place in the cross-machine direction at point A. Web flutter may occur in three modes - string- mode flutter, edge flutter or combination of both. In the string mode flutter the web behaves like a string between two rollers and is excited by movement of air in the machine direction. In edge flutter, air flow in the cross machine direction causes large amplitude of flutter at the free edges.

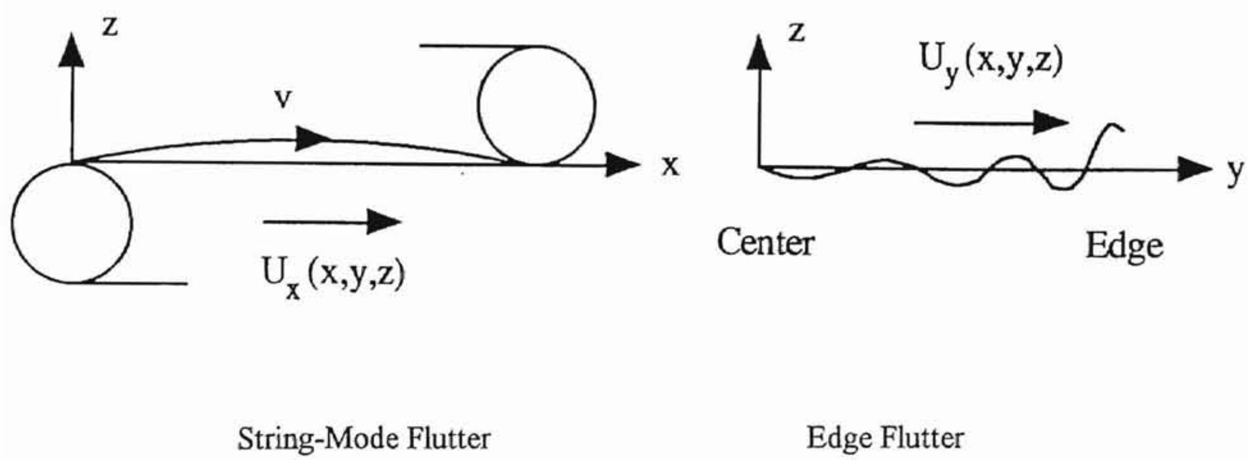

Fig. 2 Flutter Modes in Dryer Section

It is necessary to predict the critical operating conditions at which flutter onsets, and how to predict flutter amplitude and web stresses, to operate a machine as fast as possible. In order to increase machine speeds further, new and more effective ways of suppressing flutter, and if possible elimination of the problem of sheet flutter, should be explored.

Purpose and Objective

This study is related to the problem of edge flutter caused in the dryers of the paper machines and plastic web coating. In general, hot air flows from the middle section of the web towards the free edges of the web, thus causing the web to flutter like a flag in wind. Figure 3 shows the typical time series data of edge flutter due to air flow in the cross machine direction [2]. The flutter amplitude was observed to be about three times the amplitude of flutter for low air flow in the cross machine direction. Thus, the air flow alone may induce detrimental edge flutter in web machines.

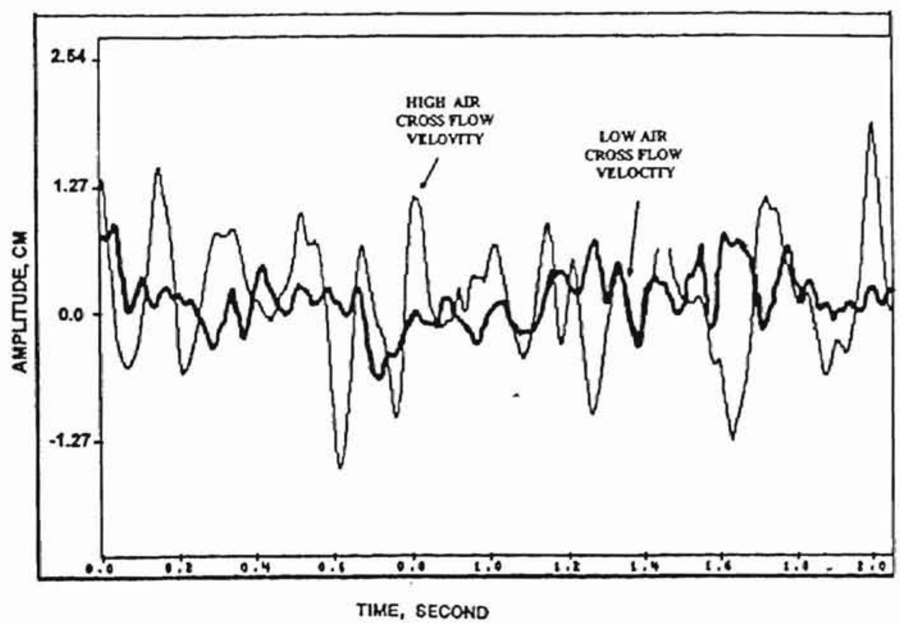

Fig. 3 On-line monitor of Sheet Flutter [2]
(Measurement of on-line flutter amplitude at Union Camp Mill by Nguyen)

In this study, a new technique of putting an asymmetrical obstruction to the air flow for the purpose of inducing tension in the slack edge and thus suppressing flutter is investigated.

The objectives for this study can be enumerated as follows :-

1. To investigate the possibilities of suppressing web flutter by asymmetrical obstructions to the air flows measures, such as changing the flow patterns by using a baffle plate.

2. To use flow visualization techniques to determine the flow patterns, and obtain understanding of the causes of suppressing web flutter.

3. To study the effect of a change in the flow rate and other variables like tension, and baffle height.

4. To estimate the tension induced in the slack edge and to compare with the stability criteria for edge flutter as developed by Chang and Moretti [3].

Organization

A literature survey, of all papers and patents giving causes of web flutter and means to reduce it, is presented in chapter II. Chapter III describes the modeling of the problem, the experimental setup used and the test procedure. A description of the experimental results and discussion is presented in Chapter IV. Chapter V gives the conclusions for this study and also suggestions for future work.

CHAPTER II

Literature Survey

In the last 25 years, different arguments were given concerning the causes of sheet flutter. Various techniques proposed or tried to prevent flutter, range from choosing the right kind of felts by Race et al [4] to the use of draw control using sensing devices, controlling sheet strength, and use of air draws and spoilers to block air in the region by Dunn and Harke [5].

Vennos and DeCrosta [6] considered air movements, induced by the carrying rolls and dryer fabric as the main cause of web flutter. The other parameters being observed by them were structure of the fabric, machine speed, width, drying temperature, and geometric arrangement of cylinders and carrying rolls. They also constructed a simulated dryer pocket and observed the axial, radial and tangential components of the flow. Race et al [4], also, reported flutter in the first dryer section of the paper machines, for relatively low speeds of around 1500 fpm. Their experiments consisted of an examination of the boundary layer of a dryer felt or fabric. Cedercreutz [7], in agreement with earlier workers in the field considered differences in the axial air speeds on both sides of the sheet to be the main cause for flutter. Majumdar [8] suggested simple mathematical models of sheet flutter. Also the interaction of the web with an air flow in the machine direction is discussed by Pramila [9, 10], Niemi and Pramila [11], Chang and Moretti [12]. The effect of air flow in the cross-flow direction is analyzed by Chang and Moretti [3, 13].

Also many mechanical means to minimize sheet flutter were invented. They are basically modifications of the basic heated roll dryer designs. Cedercreutz [7] advised the use of wrinkle irons or support rolls to hold the sheet in the open draw. DeCrosta [6, 14, 15] suggested the use of a stepped block for Coanda effect, air knife to get rid of the boundary layer of air, and vacuum devices. Edgar suggested a single felt configuration called the "Uno-Run" and asserted that it completely stabilizes the sheet against sheet flutter or billowing.

In summary, many novel ideas based on the fundamentals of fluid mechanics were suggested for suppressing web flutter. However, there is no field data available to test the validity and the effectiveness of these innovations.

Table I is an exhaustive survey of literature pertinent to web flutter - its causes and cure.

Table I

WEB FLUTTER- Causes and Cure

---

1. DeCrosta [6]

Causes :
- Windage i.e. air carried along by a drier fabric because of frictional and viscous effects.
- "Air pumping" i.e. movement of air into, and out of, the drier pocket as caused by the drier fabric.

---

2. Vennos and DeCrosta [14]

Causes:
- Excessive machine speeds(> 2000 rpm) and highly permeable dryer fabrics which cause cross-machine directional air flow in the dryer pocket.

---

3. Race, Wheeldon & Clark [4]

Causes:
- Felt speed (independent of felt surface roughness)
- Felt permeability.

---

4. Cedercreutz [7]

Causes:
- High machine speed
- Axial air streams in the dryer pockets and by differences in the axial air speeds on both sides of the sheet.

Cure:
- Use wrinkle irons or support rolls that hold the sheet in the open draws.
- Make edges of the sheet slightly heavier.
- Make changes in the clipper seam of the felt

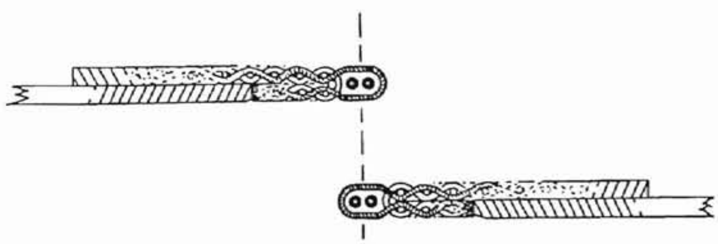

Fig.4 New 'Loop' Clipper Seam
(New seam features synthetic loops instead of metallic hooks and therefore requires no flap for reduced weight and thickness.)

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5. DeCrosta [15]

Causes:
- Kinetic energy of the boundary layer associated with the moving webs.
- Pressure buildup due to the change in direction of a moving web by a turning roll.
- Boundary layer disruption at both ends due to the compression of the fabric by the nip.
- Cross machine direction air flows in the dryer pocket.
- Non-uniform permeabilities in the longitudinal direction
- Improper tension
- Stick release mechanism between the rolls and sheet.

Cure
- Use a stepped block for Coanda effect

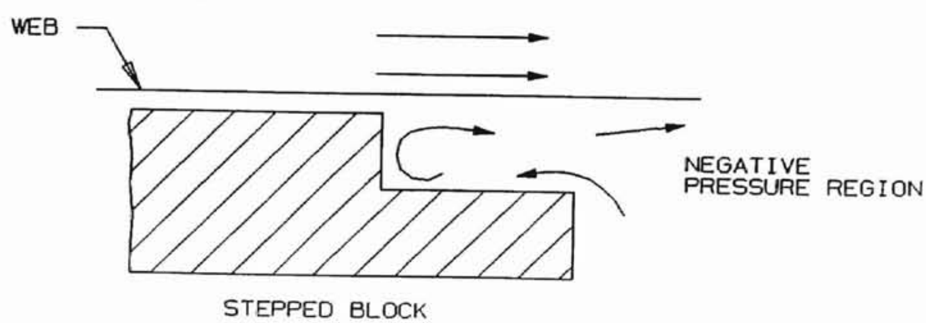

Fig. 5 The Coanda Effect

- Use air knife to get rid-of the boundary layer
- Use blowpipes operating at pressures greater than ambient to disrupt the boundary layer
- Use vacuum devices like suction pipes, vacuum boxes, vacuum rolls

---

6. Edgar [16]

Cause : •Use of new felt seam which uses synthetic hooks, which results in smoother machine operation.

---

7. Majumdar [1]

Causes:
- Passage of the felt seam
- Vibration of the dryer rolls
- Eccentricity of the rolls
- Non-uniform web tension in the cross-machine direction
- Unequal flow (and pressure) on both sides of the paper
- Axial flows induced due to pocket geometry

Cure:
- Use of the special dryers like the Papridryer which employs a high velocity hood and a suction roll to increase the drying rates about 8 times the conventional ones

---

8. Cutshall & Mardon [17]

Causes:
- Variety of cross-machine variations
- Head-box edge effects
- Machine misalignment
- Sheet wet web strength
- Dryer clothing seam disturbances
- Degree of fiber alignment

---

10. Majumdar & Douglas [8]

•Used two mathematical models to represent sheet flutter: the traveling threadline model and the flexible membrane model; each model then predicts the condition for resonant oscillations.

---

11. Edgar [18]

Cure: •A single felt configuration in the first dryer section called "Uno-run" which completely stabilizes the sheet against edge flutter or billowing in the early part of the dryer sections. The Uno-Run involves running a dryer fabric through the dryer section such that it follows the sheet path. The sheet lies between the fabric and the top dryers and rides on the outside of the fabric around the bottom dryers.
•This method keeps the tension along the width of the web to be constant

---

12. Bringman & Jamil [19]

Causes: •Pumping action of air
•Variable longitudinal stretch across the sheet width
•Uncontrolled air turbulence in dryer pockets caused by the highly permeable open felts, felt seam, cylinder head bolts etc.
•Adhesion tendency of the sheet to the cylinder or to the felt.
•Sheet slackness in unsupported draw.

Cure: •Increase sheet tension
•Increased wet sheet strength by increasing the chemical pulp content
•Reduce machine speed
•Shrouding cylinder head bolts, air disturbances in dryer pockets
•Use less permeable felts
•Reducing open draw between top and bottom cylinders
•Using serpentine felt arrangement

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13. Palazzolo [20]

Cure: •Usage of serpentine felt run (Uno-run) dryer felt arrangement with low felt permeability

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14. Pramila [9, 10]

•Formed an analytical model by combining the theory of hydrodynamics with theory of the dynamics of axially moving material. The critical velocities were about 15 to 30% of the values predicted by neglecting the interaction between sheet and surrounding air. The natural frequencies predicted earlier are 400% greater than the values shown by this model which matches with the true values.

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15. Niemi & Pramila [11]

•Transverse vibrations of an axially moving membrane submerged in an ideal fluid is studied using Finite Element Method; They considered two additional terms due to convective acceleration.

---

16. Hill [21]

Causes: •Excessive air pumping
•Over-pressurization of the hood
•Improper control of the dryer steam pressure in Uno-run group
•Poor drainage of the dryer in Uno-run group

Cure: •Use of air deflector
•Blow-boxes
•Using thin felt
•Using lick-down transfer in between two different sections
•Using a felt with less permeability

---

17. Chang & Moretti [3]

•Conducted analytical and experimental studies showing the interaction of the web with the surrounding air. Developed empirical equations to assist in the prediction of the critical conditions for web flutter. Suggestions are made for design changes to minimize flutter problems:-

Since the local interaction of the free edge is so important, therefore one way of controlling flutter is by changing the ventilation system by supplying more drying air at the center and less at the edges.

Since unequal flow speeds (or pressures) on the two sides of the web is one of the reasons for flutter therefore, an obstruction near the free edge might help.

---

18. Edgar [22]

Cause: •The boundary layer of air associated with the web at higher speeds

Cure: •Using ventilating ducts to doctor-off the boundary layer building on the inside of the fabric as it travels around the dryer
•Using ventilating rolls to provide a firm surface behind the fabric
•Use combined blowing and vacuum roll. In this case the ventilating chamber is divided into two compartments, a vacuum side and a pressure side. Air is both exhausted and injected by the roll, thus alleviating the problem of axial air flow to the sides of the machine
•Using single felting arrangement

•Using grooved bottom cylinder(unheated)

---

19 Fagerholm [23]

Causes: •Fabric parameters like air permeability, fabric structure, void volume, yarn type, roughness.
•Machine speed
•Length of the free draw
•Blow-box settings

---

20. Luciano [24]

Cure: •Using unirun or single felt configuration
•Using blow box, installed inside the unirun fabric between the top and the bottom dryers
•Creating a negative pressure under the fabric which draws the sheet tightly to the dryer fabric

---

21. Adams [25]

Cause: •Inter-related effects of webs on rolls and the undesired profile produced by them through the mechanisms of web-roll interaction, spreading and reel effects (also talks about the fundamental law of web tracking, traction, importance of roll geometry etc.)

---

22. Nguyen [2]

• Development of portable flutter probe using an infra-red reflective displacement sensor to monitor the on-machine flutter amplitudes and frequencies.

---

23. Dunn and Harke [5]

Causes: •Web transfers between the process steps which are usually of the open-draw types is the main reason for operational problems and web defects.
Cure: •Draw control at the open -draw transfer using sensing devices, regulation of drives etc.
•Control the sheet strength by white water chemistry and micro-bacteria control
•Using transfer fabric or felt in combination with suction boxes to directly transfer sheet from one section to another

•To use air draws and spoilers to block air in the nip between roll and fabric

---

24. Chang, Cho, Moretti [13]

• Made a traveling wave analysis based on the linear potential flow theory, and predicted the critical flow velocity, wave velocity, wavelength and flutter frequency

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CHAPTER III

EXPERIMENTAL SETUP AND PROCEDURE

Infinite Loop and Wind Tunnel

An infinite loop machine was used for the experimentation. All the experiments were conducted with the machine speed being zero. The web passed through the slots on the side walls of the wind tunnel. A paper tape was wound around the rollers to prevent web slippage on the rollers.

On this machine a wind tunnel as shown in figure 6 & 7 was mounted. The size of the test section of the wind tunnel was 12" x 12" x 22" and was connected to a 4' long tapered duct. In order to isolate the wind tunnel from the vibration of the blower, thin plastic webs were used to join them. The duct was then suspended freely from a beam passing near the ceiling of the room. Air flow through the tunnel was controlled by using the opening of damper. Air velocity was changed in the range of 800 ft/min. to 3600 ft/min.

The velocity profile of the air inside the wind tunnel was measured by using a Pitot tube. Manometers with least count of 0.005 or 0.01 inches of water were connected to the Pitot tube to measure the dynamic pressure.

Web Support and Tension Distribution

The downwind edge of the web can be made slack by misaligning the support rollers. The second method was to attach the web on a pre-stressed, steel tape measure.

However, since non uniformity of tension across the web is one of the main causes for sheet flutter, it was decided to keep the web tension in the cross machinedirection constant. An upwind edge protector was installed at one of the edges of the web, in order

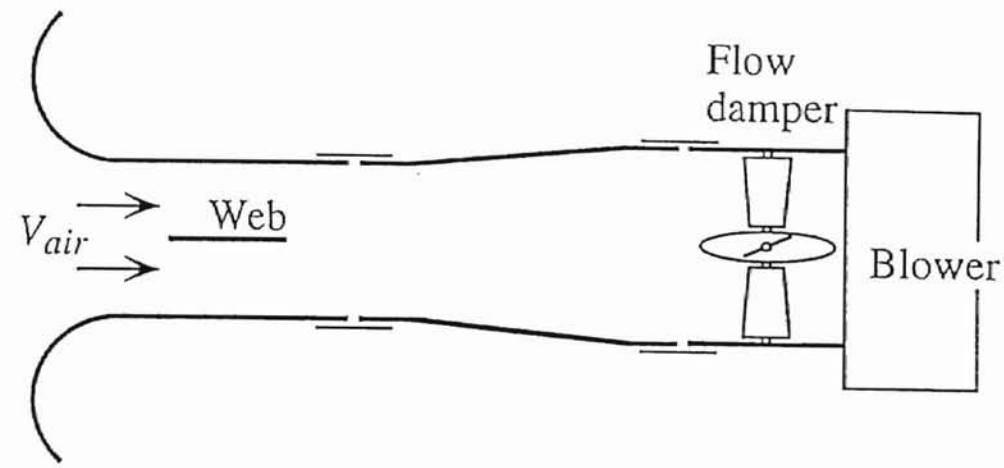


Fig. 6 Wind Tunnel (Front View of the Test Setup)

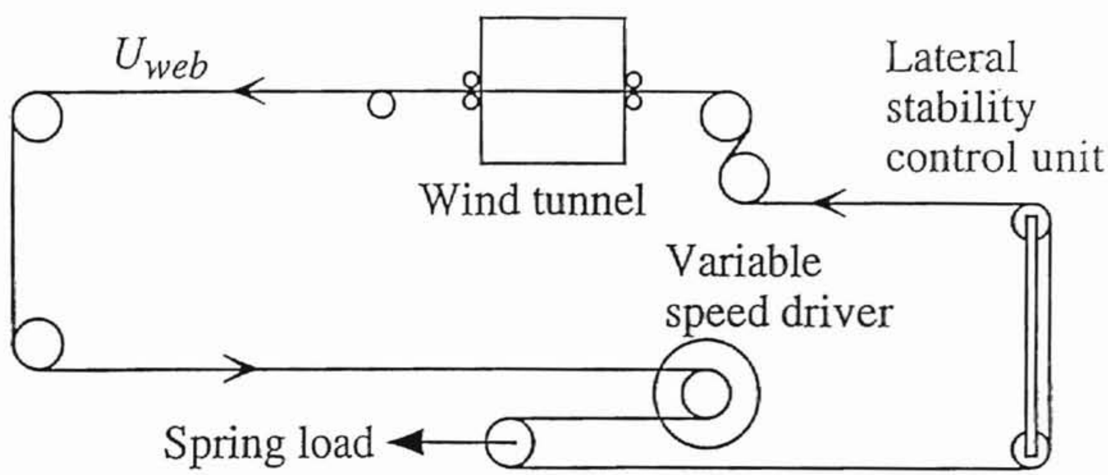


Fig. 7 Infinite-Loop Machine (Side View of the Test Setup)

to prevent the vertical deflection of the upwind edge. All the results reported were obtained using this method.

Instrumentation

Two laser vibrometers(Polytec OFC-2600) were used to measure the wave properties of the edge flutter (frequency, amplitude, phase and wave speed) along the flow direction. Near the normal incidence of the laser beams, the beams reflected at the top surface of the wind tunnel were so strong that the vibrations of the web could not be properly measured. In order to prevent that problem, and to adjust the location of the measuring points, the vibrometers were kept in a slightly tilted position.

Data Acquisition and Analysis

Throughout the experiment, all the dominant frequencies were below 200 Hz. Therefore, the signal from each laser vibrometer was filtered by a low pass filter with a cut-off frequency of 200 Hz. The filtered signal was sampled by a data waveform analysis instrument DATA 6100 - the number of sampling points with a time period of 1 ms was 4096. The two filters were calibrated with a cut-off frequency set at 200 Hz. During the experiments, the peak to peak amplitudes, RMS amplitudes, spectral analysis peaks and phase difference were recorded for each test.

Typical time history and velocity spectra (not averaged) are shown in figures 8 and 9. The phase difference between the signals could be determined by comparing the time histories, provided their signals become steady. Also the cross-correlation method or the spectral method could be used to measure the phase.

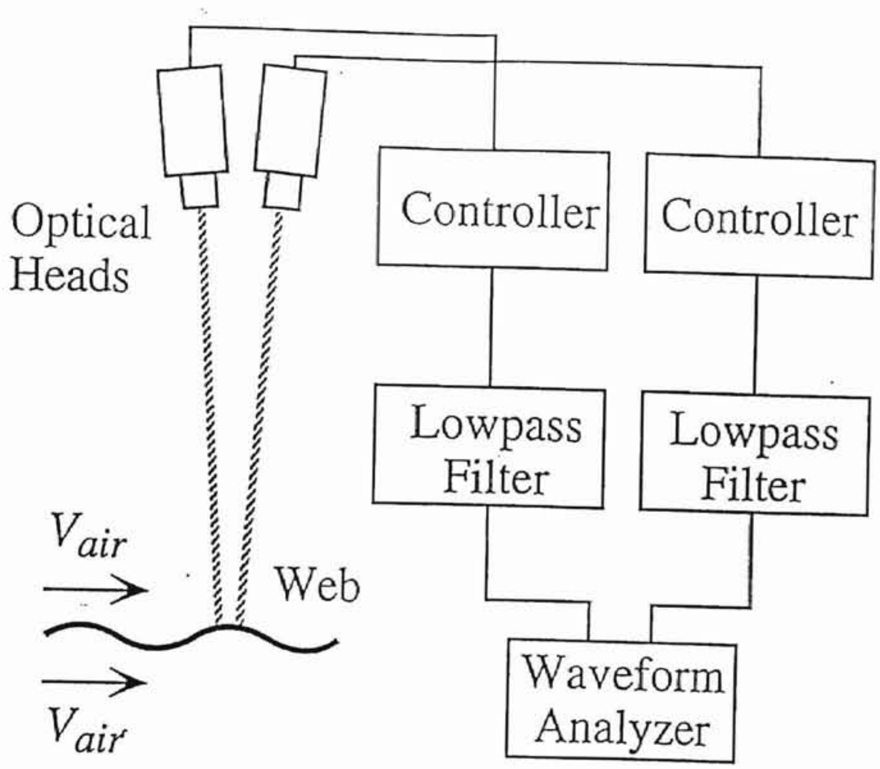


Fig. 8 Instrumentation

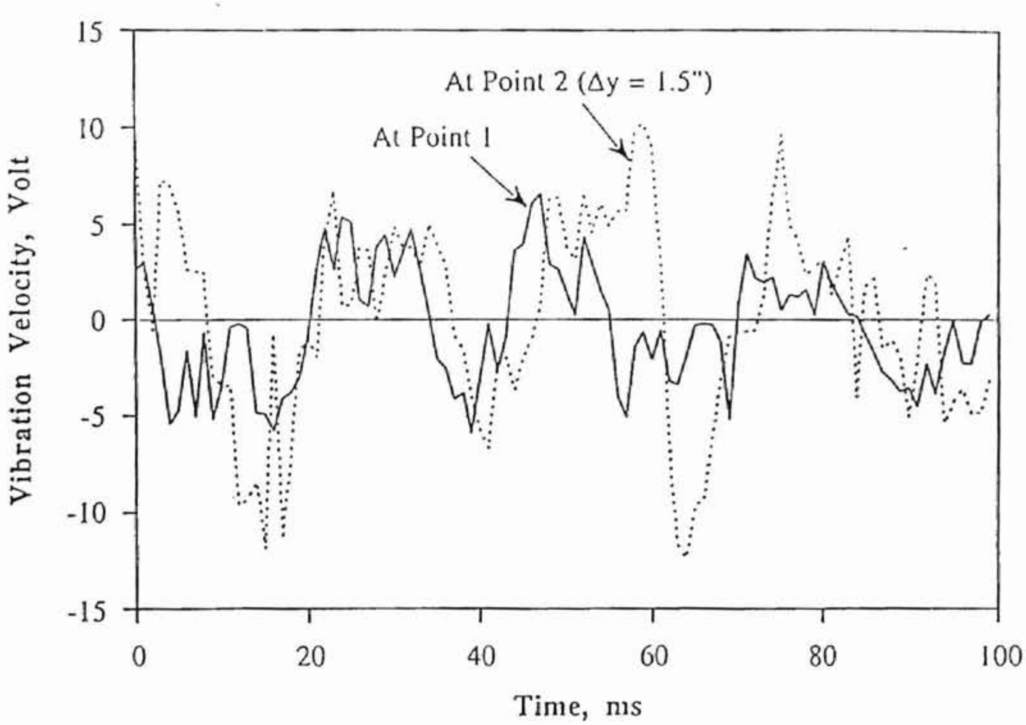


Fig. 9 Time History

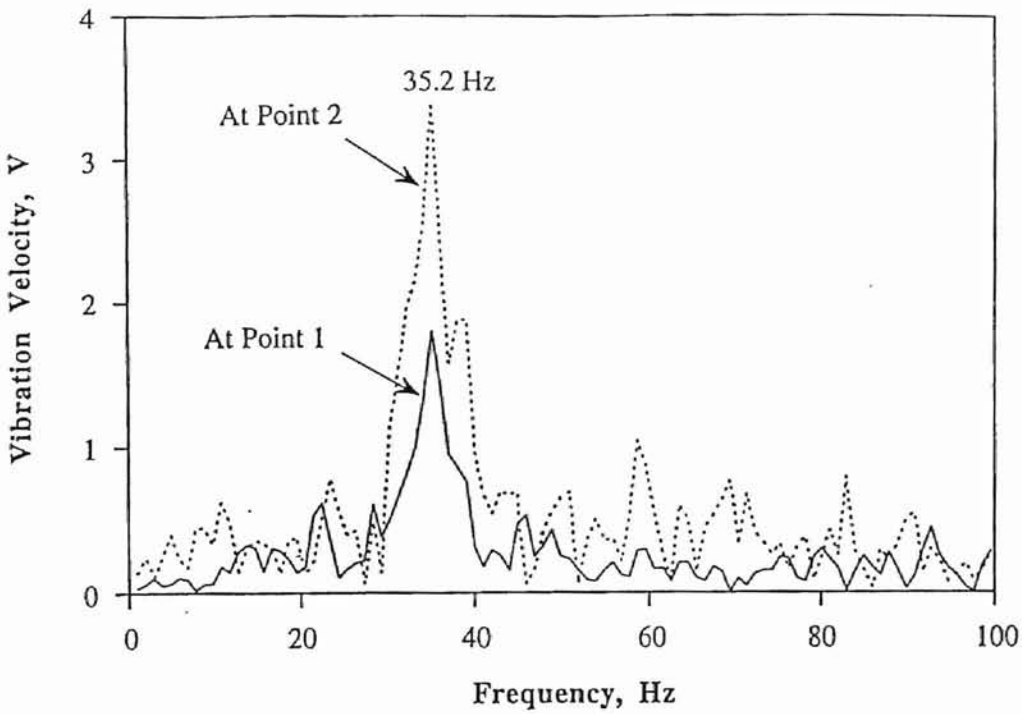


Fig. 10 Velocity Spectra
(1 V = 125 mm/s)

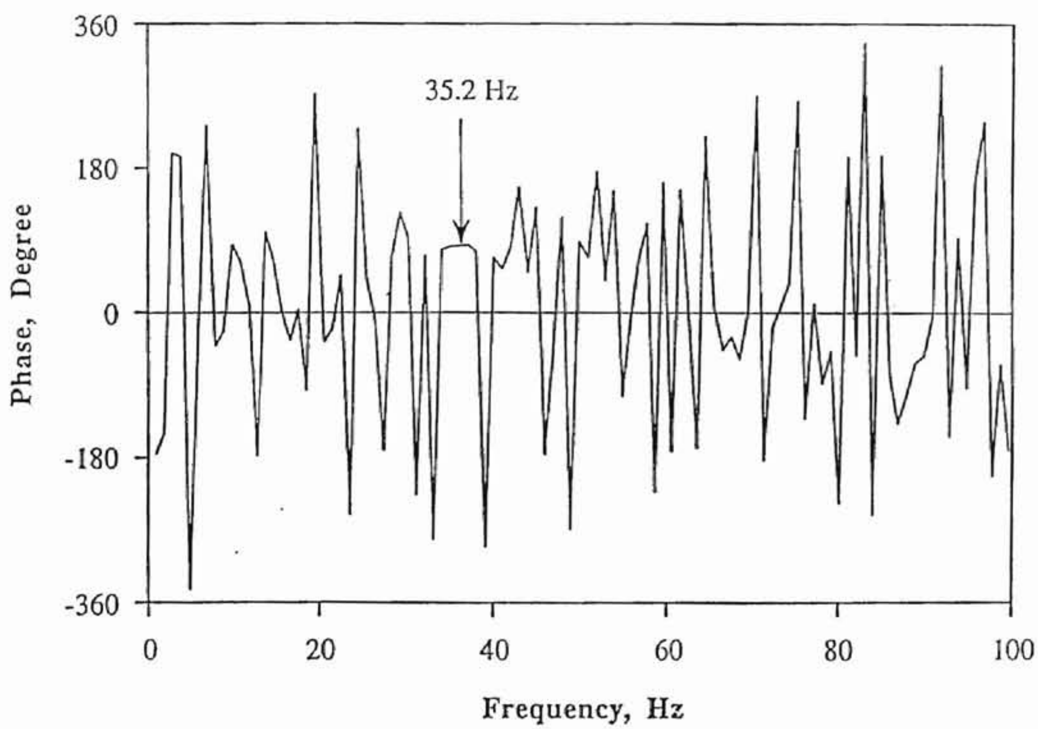


Fig. 11 Phase Spectra

CHAPTER IV

EXPERIMENTAL ANALYSIS

Approach to the problem

The effectiveness of the method of introducing an unsymmetric obstruction in the flow field was studied completely by the following steps:-

Step 1. Complete literature survey for full understanding of the problem of edge flutter, and the methods used up-to-date to prevent it.

Step 2: Perform preliminary experiments to understand the behavior of the web when the flow is obstructed by blockage of different configurations.

Step 3. Determination of the most effective region for the blockage or baffle plate to suppress flutter.

Step 4. Conduct experiments in the most effective regions as obtained from step 3 by varying the angle of the baffle plate with respect to the direction of the flow.

Step 5. Flow visualization tests to perceive the flow patterns inside the test region of the wind tunnel.

Step 6. Study the effect of change in flow rate (by controlling the opening of the flow damper) and angle of the baffle plate at the downwind edge.

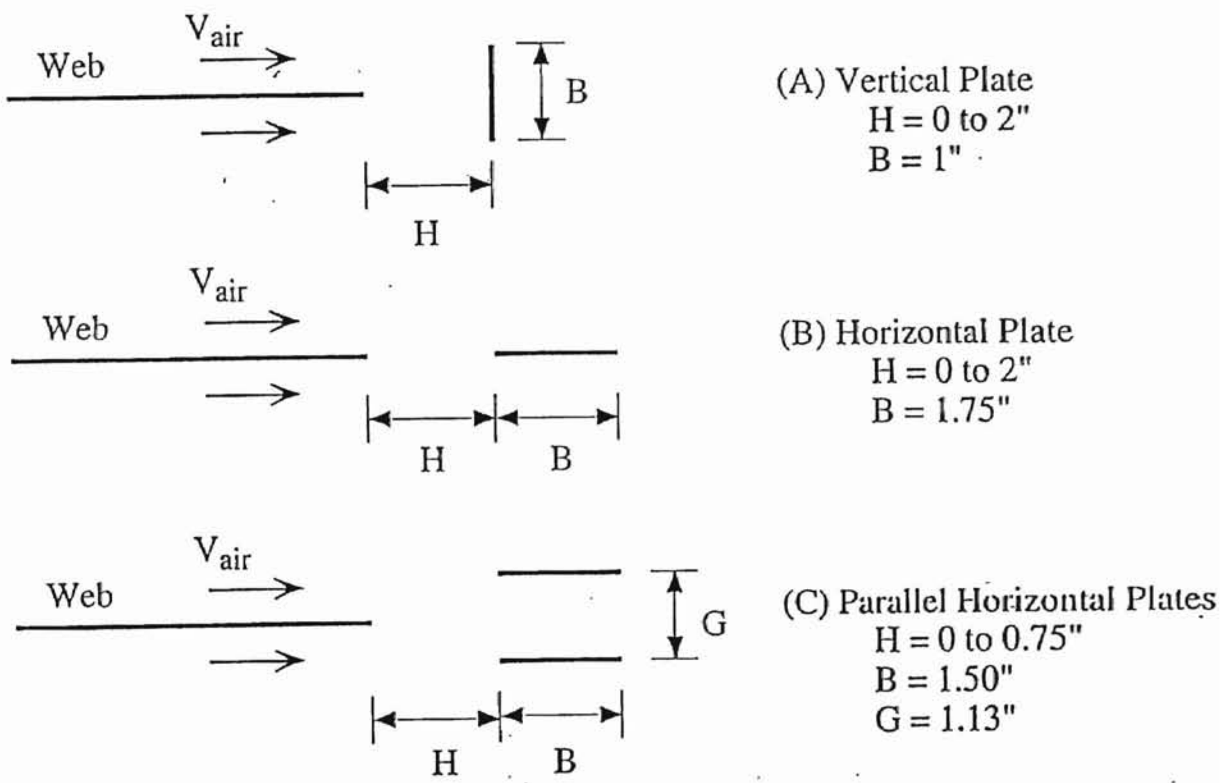
Step 7. Study the effect of change in height of the baffle plate in controlling flutter.

Step 8. Study the effect of change in tension on web flutter.

Step 9. Measurement of static pressure difference and curvature near the downwind edge (slack end) of the web and to compare with the stability criteria as developed by Chang and Moretti [27].

I. **Preliminary tests to understand the behavior of the web when the flow is obstructed by the blockage of different configurations.**

The following methods were tested as preliminary experiments to understand the effect of different baffle plate configurations on web flutter.



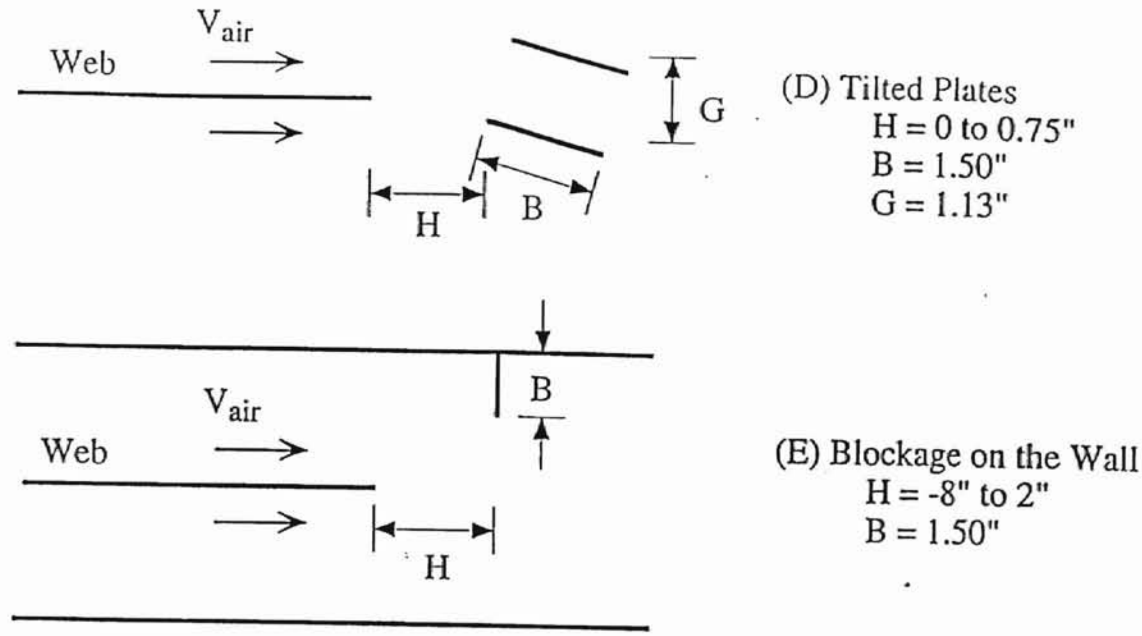


Fig. 12 Effect of different baffle plate configuration on web flutter

Setup **(a)** and **(b)** : When the distance between the free edge of the web and the plate was close (less than a quarter of an inch), edge flutter became more severe; otherwise, the plate had no appreciable effect on the edge flutter.

Setup **(c)** : No appreciable effect on the edge flutter was observed.

Setup **(d)** : When the plates were tilted a few degrees, the free edge of the web deflected with substantial increase of local tension and the edge stopped fluttering. When the flow velocity was increased, the static deflection was increased without flutter. This method may be helpful to suppress edge flutter by tightening the slack edge.

Setup **(e)** : When the blockage was near the free edge, nearly the same effect as described in Setup **(d)** was observed. At other locations, the blockage had minor effect or made the problem worse.

II) Tests to determine the most effective regions for suppressing web flutter. (Figure 13)

From the earlier results it was concluded that setup (E), or a blockage on the wall, is the best configuration that helps in preventing web flutter. So from this point onward all experiments are conducted with this configuration.

The test region was marked with a number line such that the position of baffle can be clearly defined with reference to the downwind edge (marked as zero). Readings were taken with the baffle plate being moved beyond the downwind side and also towards the upwind side. A pitot tube positioned below the web was used to measure the dynamic pressure or velocity in the test region below the web. The data from the two laser-Doppler sensors were passed through a low pass filter and then processed by DATA 6100 (waveform analysis instrument).

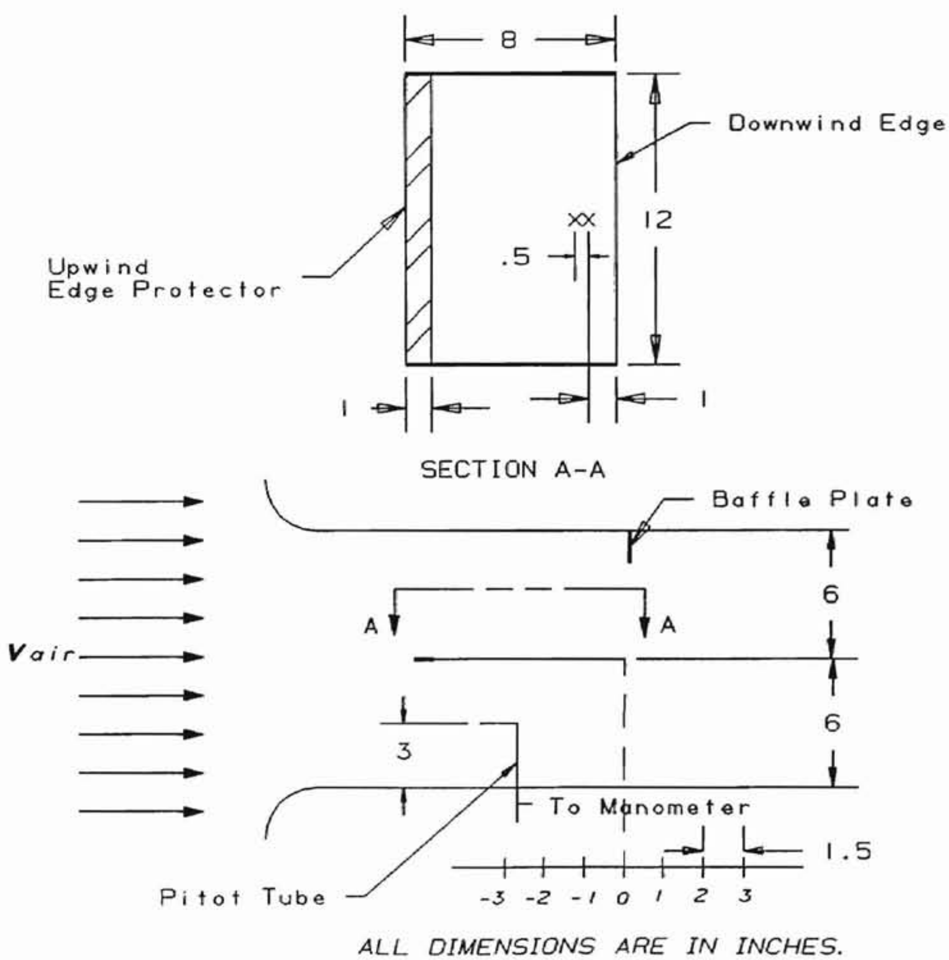


Fig. 13 Experimental Setup

• *Position of Baffle Plate v/s Manometer reading*

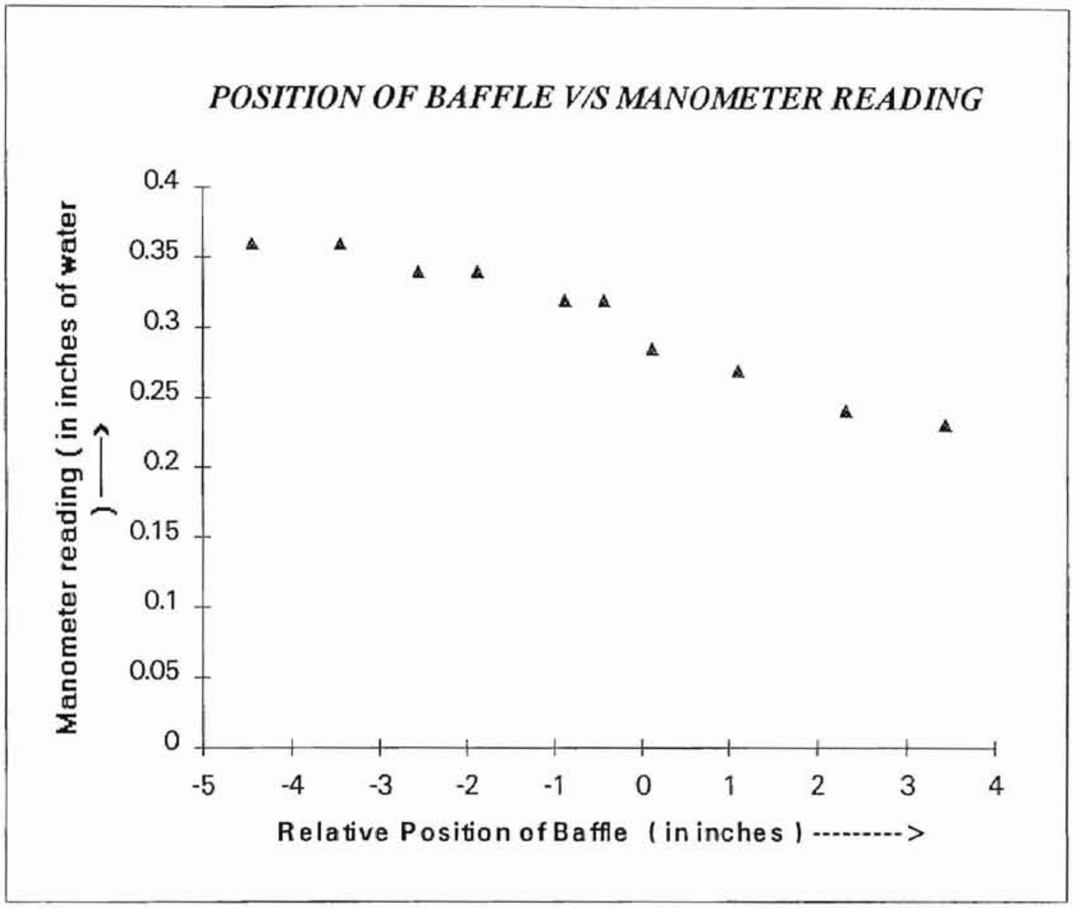


Fig. 14 Manometer Reading (Dynamic Pressure) for various position of the baffle plate with respect to the downwind edge

From the above graph one can see that as the baffle is brought just beyond the downwind edge there is a sharp drop in the manometer reading. This may be because, as the baffle is brought beyond the slack edge of the web it deflects the flow towards the region below the web. Thus, the dynamic pressure reading as shown by the manometer and being measured by the pitot tube kept below the web reduces suddenly.

• ***Position of Baffle Plate v/s RMS Amplitude.***

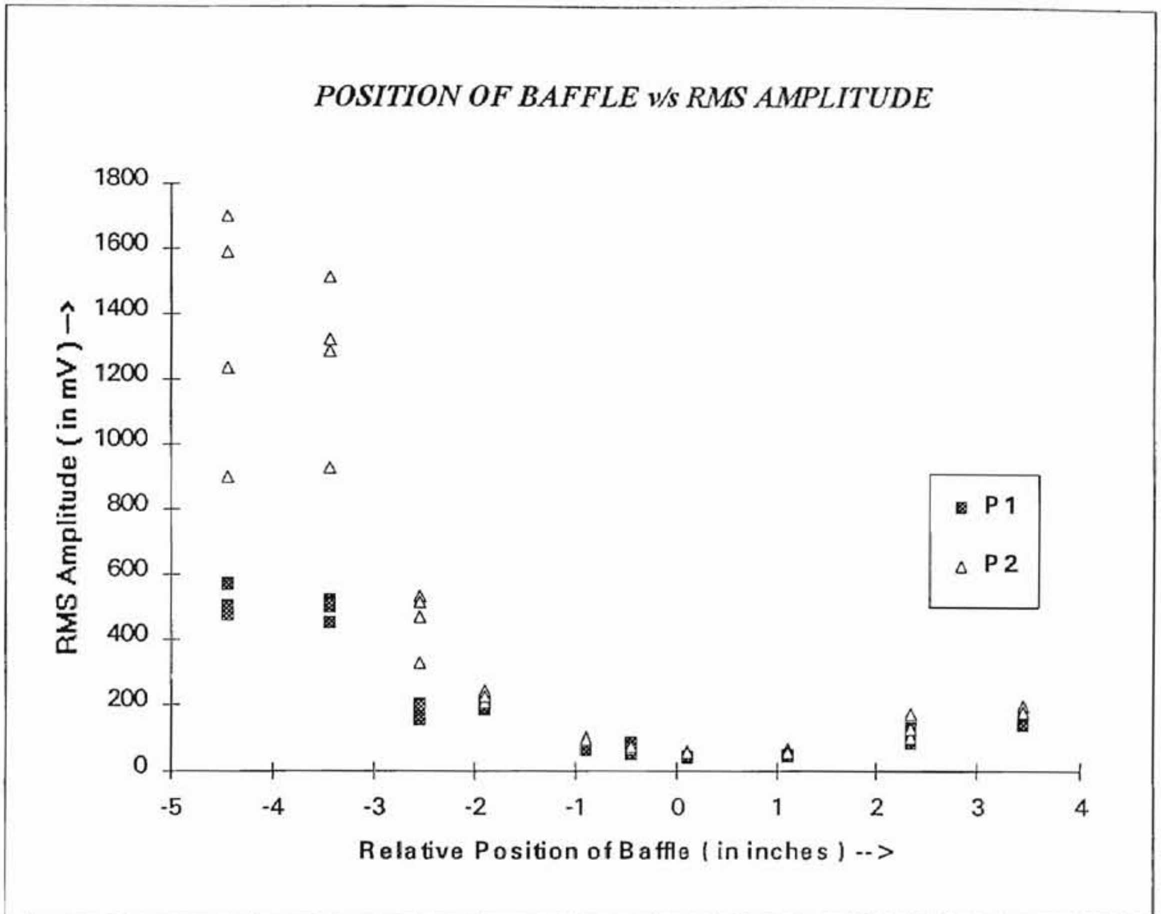


Fig. 15 RMS Ampitude of flutter velocity for various position of the baffle plate w.r.t the downwind edge
(P1 and P2 corresponds to the readings from the two laser-Doppler sensors. RMS velocity amplitude of 1 V = 125 mm/s)

From the above graph, one can see that the RMS amplitude observed is a minimum when the baffle plate is put at the downwind edge. Also, the RMS amplitude, when the baffle is put beyond the downwind edge, is less compared to the case when it is put towards the upwind edge. This is because as one puts the baffle in the region around the downwind edge or beyond it, a tension is induced in the web which suppresses the web flutter. However, when the web is brought close to the downwind edge it creates turbulence in the wind tunnel and thus there is a rapid increase in the RMS velocity.

• *Position of Baffle Plate v/s Velocity.*

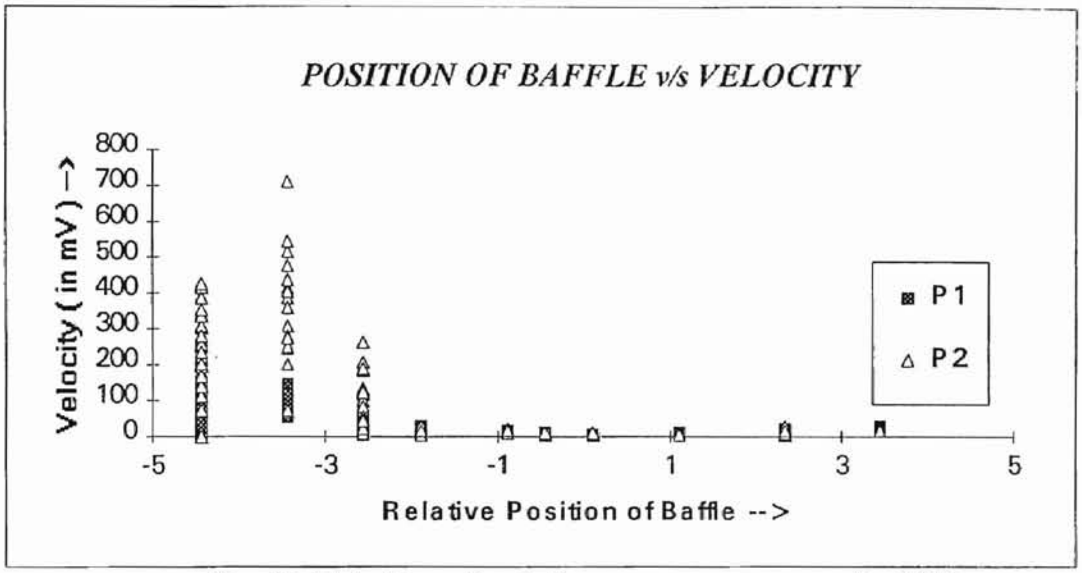


Fig. 16 Velocities of main frequency componens after FFT
(P1 and P2 corresponds to the readings from the two laser-Doppler sensors. RMS velocity amplitude of 1 V = 125 mm/s)

This graph shows the velocities of the dominant frequencies, as seen by the Fast Fourier analysis of the data obtained from the two sensors. It resembles the plot obtained between the RMS amplitude of velocity and the position of baffle plate.

- *Position of Baffle v/s frequency.*

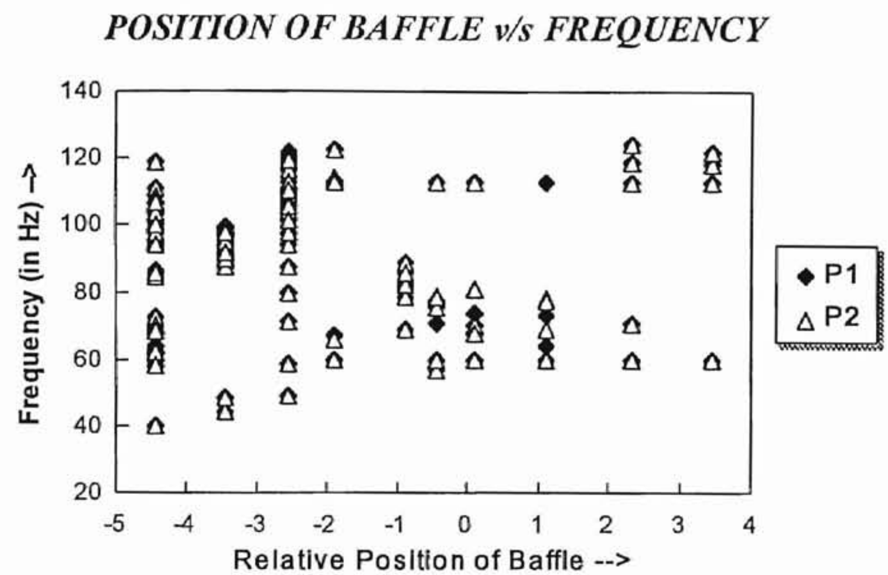


Fig. 17 Dominant frequencies after FFT for various position of the baffle plate w.r.t the downwind edge
(P1 and P2 corresponds to the readings from the two laser-Doppler sensors. The band of dominant frequencies narrows down if the baffle plate is placed near the downwind edge- Position 0)

As shown in the graph, as the baffle plate is moved from a region beyond the trailing edge of the web and brought close to the web, the number of dominant frequencies of web flutter increases. Also, as one moves from the downwind edge of the web to the upwind edge, one can see that there is no correlation between the dominant frequencies of the two points from which data is collected using the two laser-Doppler sensors. This can be explained by the fact that when the baffle plate is around or beyond the downwind edge, it deflects the flow towards the web and thus inducing tension in the web. The effect of this induced tension is the reduction in the number of dominant frequencies. However, when the baffle plate is still brought closer to the upwind edge of the web, it deflects the flow below the web and acts as a source of turbulence. Because of this turbulence, there exists no correlation between the frequencies as obtained from the two points.

- *Position of Baffle v/s Phase*

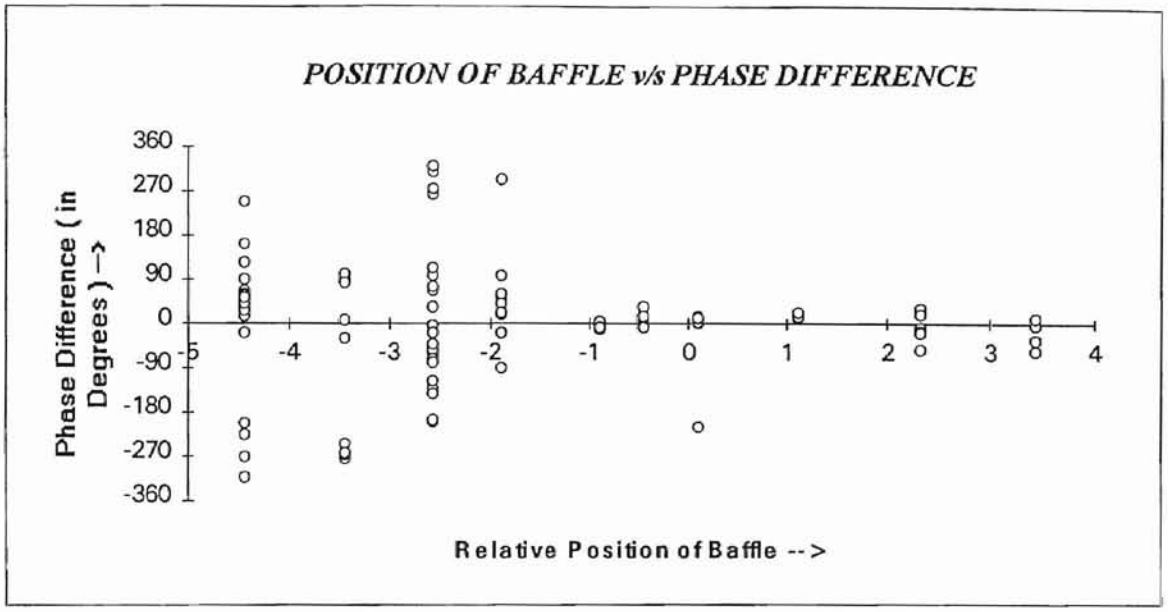


Fig. 18. Phase difference between the dominant frequencies of the two laser-velocity sensors for various position of the baffle plate w.r.t the downwind edge

As seen from the above figure, the phase difference between the two points from which data are collected using the two laser-velocity sensors is much less when the baffle plate is kept beyond the trailing edge or near the trailing edge of the web. However, as the baffle plate is brought closer to the upwind edge of the web, the phase difference increases drastically. This behavior can also be explained by the same reasoning as explained for the position of baffle versus frequency curve.

III) Experiments conducted in the most effective regions as determined by the earlier set of tests, by varying the angle of the baffle with respect to the direction of flow. (Figure 19)

In this set of experiments the baffle plate is tilted at different angles around the downwind edge to determine the most effective angle for suppressing flutter. The instrumentation and data acquisition system used for the previous tests are used.

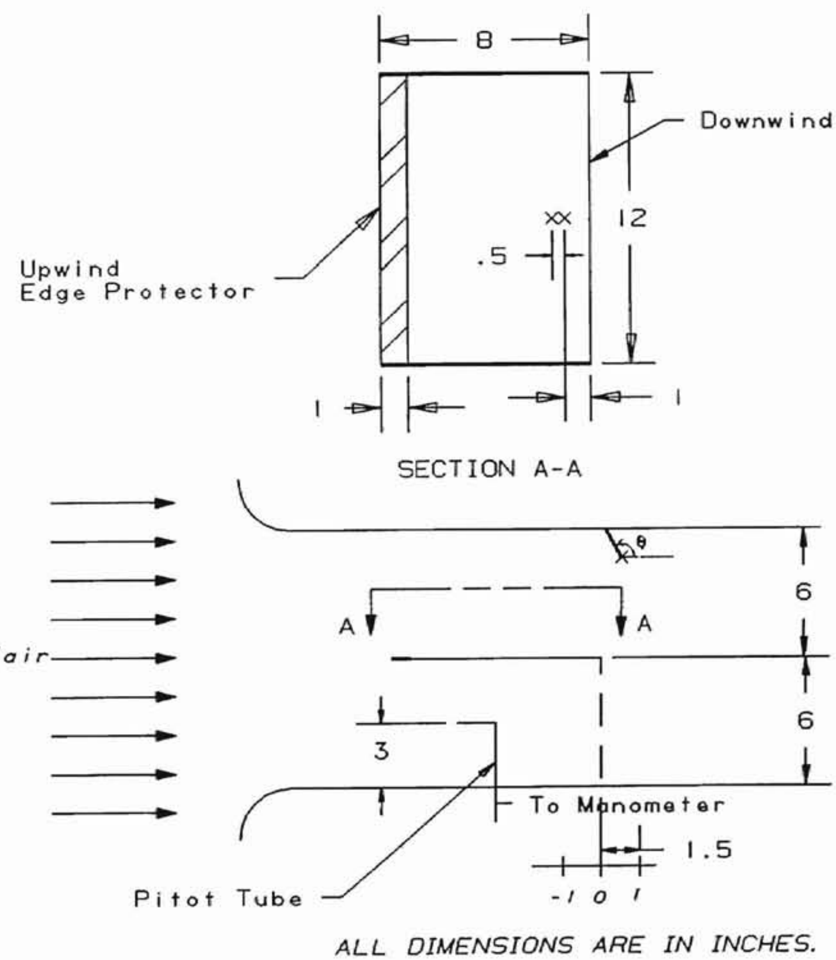


Fig.19 Experimental Setup

• *Angle of Baffle v/s Manometer Reading.*

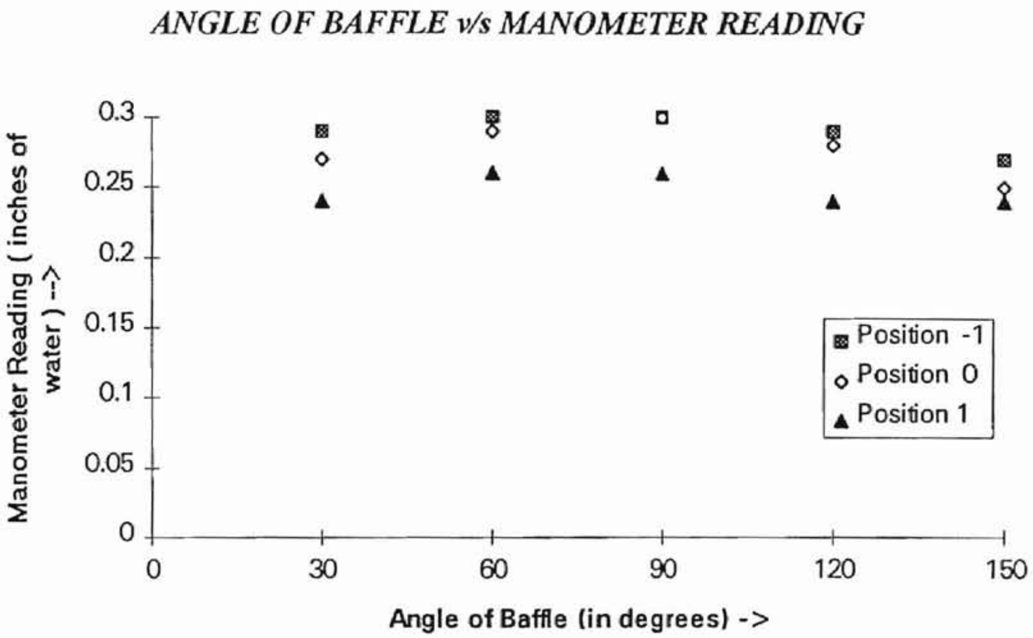


Fig. 20 Manometer reading (Dynamic pressure) for various angles of baffle in the region near the downwind edge
(Position 1 - 40 mm beyond the downwind edge, Position 0 - Downwind edge Position -1 - 40mm towards upwind edge from position 0)

From the above test it can be seen that at position -1 (40 mm or beyond the downwind edge) and at position 0 (downwind edge), there is maximum dynamic pressure reading. This indicates that for those regions and for baffle angle of 90 degrees the flow velocity below the web is maximum.

- *Angle of Baffle v/s RMS Amplitude Velocity.*

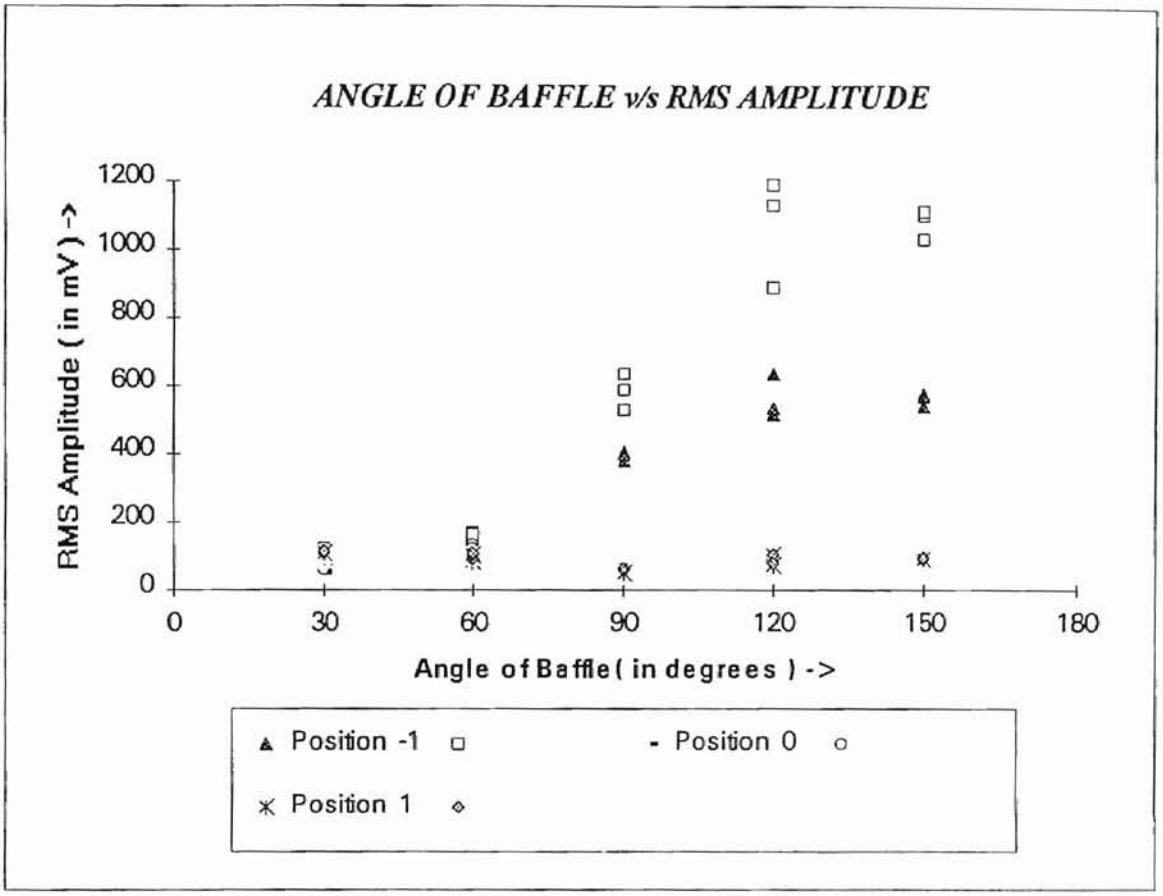


Fig. 21 RMS Amplitude of flutter velocity for various angles of the baffle plate at the most effective regions

As seen from the above graph, the RMS amplitude of flutter velocity increases with an increase in the angle of the baffle. But, close observation of the graph shows that at position -1 the RMS amplitude is about ten times the RMS amplitude for the other two positions. This is just contrary to what is expected to happen. In fact what is expected is that when the angle of the baffle is about 90 degree, it is going to induce a curvature in the web the web and thus inducing a tension in it. This induced tension causes decrease in the RMS amplitude of the web flutter. Thus, it is anticipated that as the angle of the baffle is changed from 90 deg. the RMS amplitude of velocity should increase unlike as observed by the above graph.

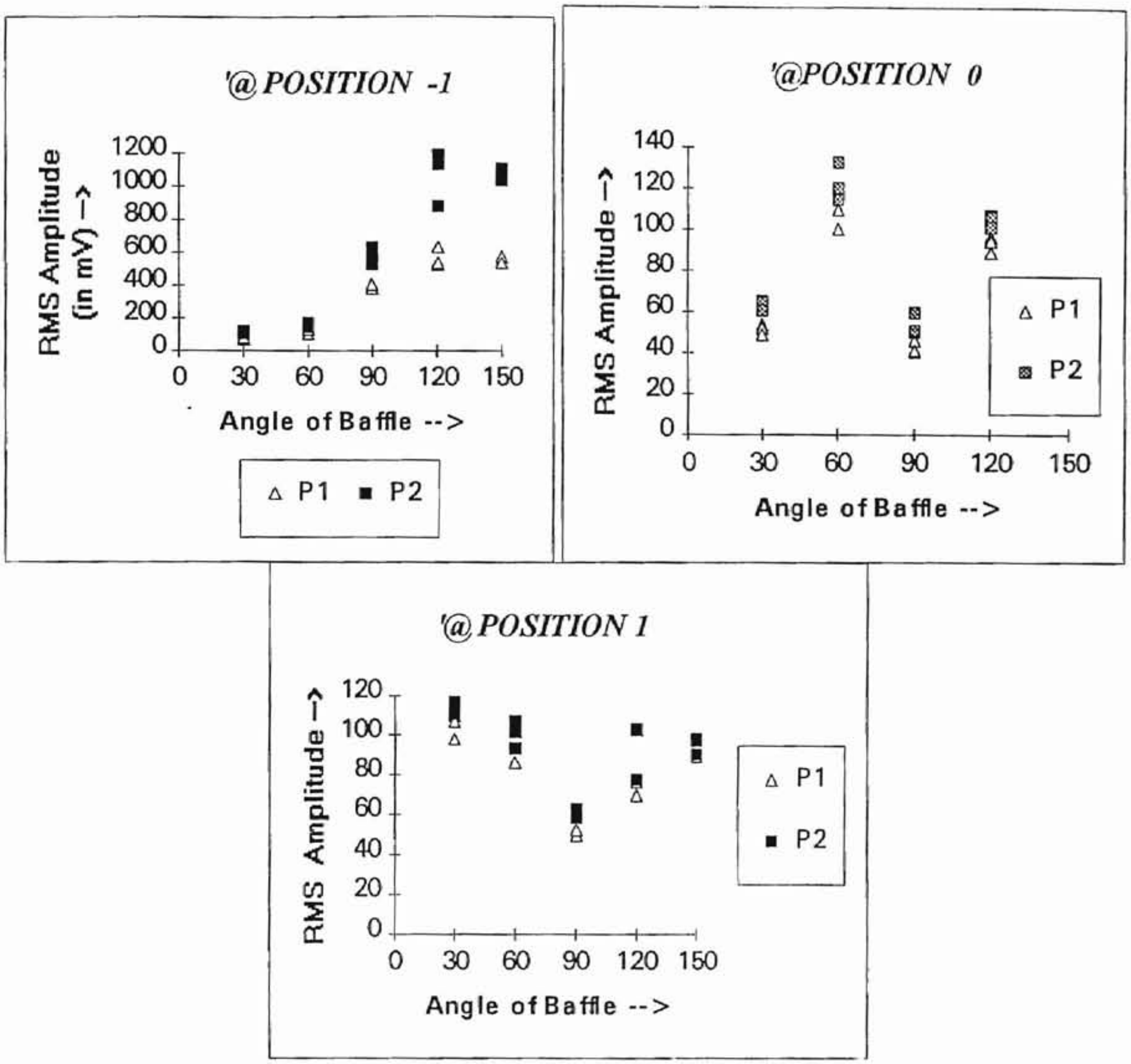


Fig. 22. RMS amplitude with varying baffle angle shown separately at 3 different positions.
(P1 and P2 corresponds to the readings from the two laser-Doppler sensors.)

The three graphs are plotted by taking the data from the plot Angle of baffle v/s RMS amplitude (Fig. 21). At position -1, for baffle angle of 90 degrees and beyond, the RMS amplitude increases by about 10 times compared to the other two positions. This might be because of erroneous data as at position -1 the laser velocity sensors were partially obstructed by the baffle plate at angles beyond 90 degrees. More improvised tests need to be done at this region to confirm the above effect.

• *Angle of Baffle v/s Frequency.*

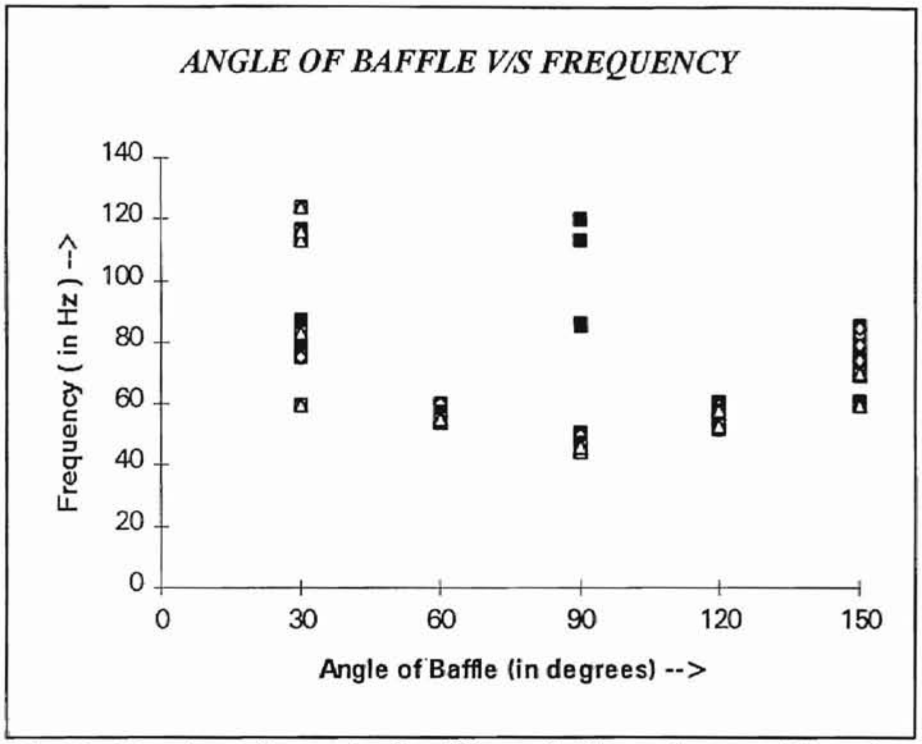


Fig 23. Dominant freqencies for different baffle angle at positions close to the downwind edge

The above graph shows the Fast Fourier transform as performed on the recorded waveform of the data as obtained by the two laser-velocity sensors.

- *Angle of Baffle v/s Phase difference.*

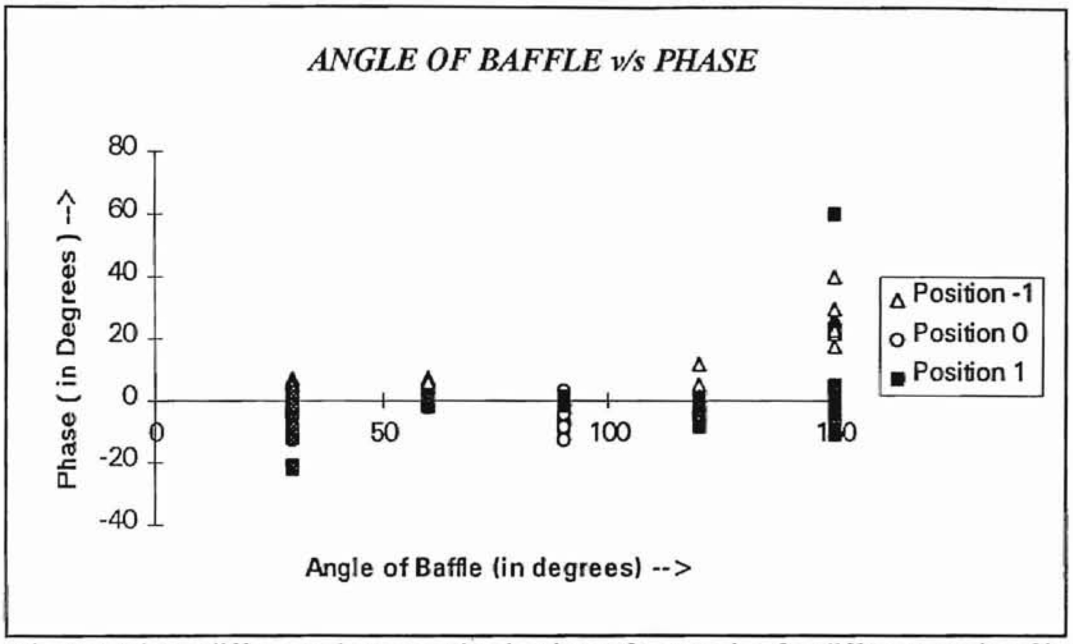


Fig. 24 Phase difference between the dominant frequencies for different angle of baffle at various baffle positions

As can be seen from the above graph, around 60 to 90 deg. there is minimum phase difference between the data of the dominant frequencies as obtained by the two different position of the laser-velocity sensors. When the angle of the baffle is increased, the phase difference increases as there is less correlation between the waves' properties as obtained at the two points.

IV. Flow Visualization

It is possible to use flow visualization techniques to determine the flow patterns . The idea is to analyze the flow pattern in the wind tunnel and thus verify whether the obstacle in the form of baffle plate actually induces the tension as predicted by the earlier tests for suppressing web flutter. We are interested in the path line traversed by a given fluid particle in some specific region. The following methods were selected for trials :

i) ***Tufts Method*** :

The usual material for tufts is tufted nylon yarn which when unstretched contracts to a fraction of its stretched length. The idea is to create a grid in the cross-sectional area of the wind tunnel using fine wires like wires of fishing nets. The tufts can be distributed in this grid and thus the flow pattern in the c/s area of the tunnel can be found.

ii) ***Dry Ice***(liquefied CO_2) :

The dense vapors of dry ice can follow the patterns of flow and thus can show us how the flow is deflected by the baffle plate for various configurations.

iii) ***Titanium Tetrachloride***($TiCl_4$) :

$TiCl_4$ if applied to the edge of the upwind edge protector it reacts with the water-vapor in the air of the wind tunnel and produces a dense fog which is visible by scattered light.

Among these methods the tufts method was tested for flow visualization. The region of interest was selected to be close to the baffle plate. In this method piano wires of around 0.06 inch was used and put in horizontal positions in arrays close to the baffle. Tufts made of nylon yarn was glued to the piano wires in such a way that they could also rotate about there axes. Then photographs were taken to understand the flow patterns.

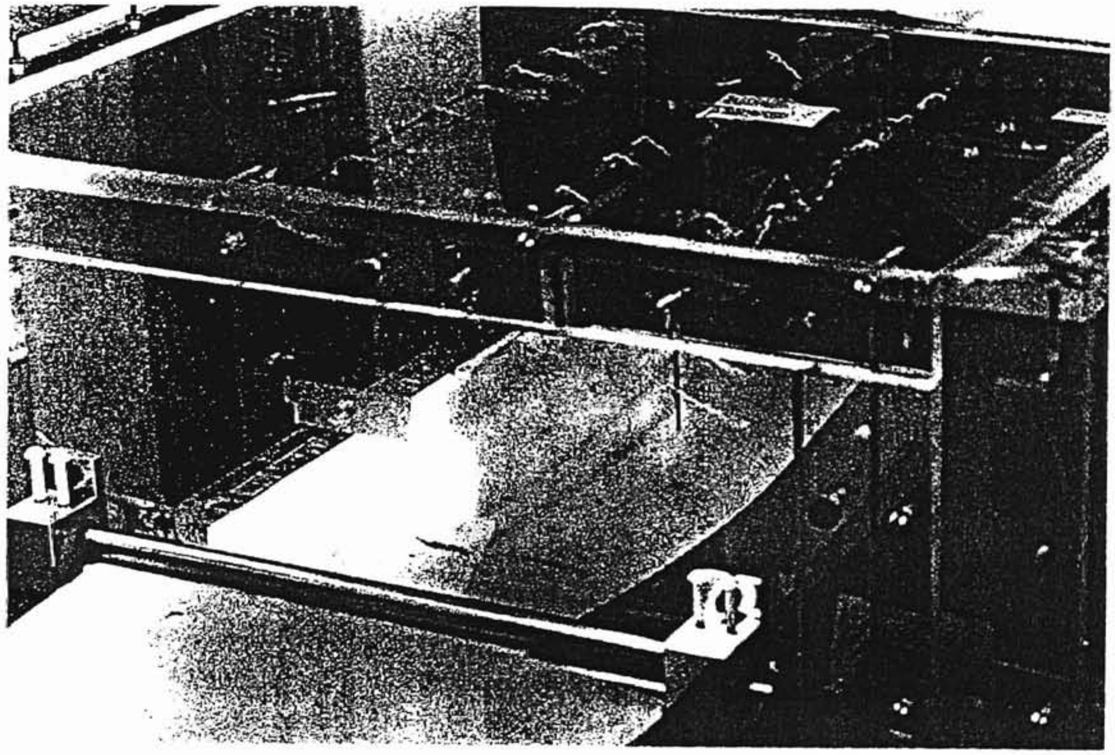


Fig. 25 Flow visualization by Tufts method

It was observed from the photographs that the baffle plate forces the streamlines closer in the region near the baffle. The baffle plate acts as a source of asymmetry in the flow stream and forces the flow patterns to modify itself between the two regions - above and below the web. There is a rise in pressure on one side of the web, which is the reason for the curvature in the web and thus the tension induced in it. The rear face of the baffle has recirculation, as can be seen from the reversed position of the tufts in that region. Sometimes the tufts in the back region starts rotating about their axes be due to a vortex formation in the wake.

V. **Effect of the change in flow rate and Angle of the Baffle on Web flutter**

- *Flow rate v/s Manometer reading.*

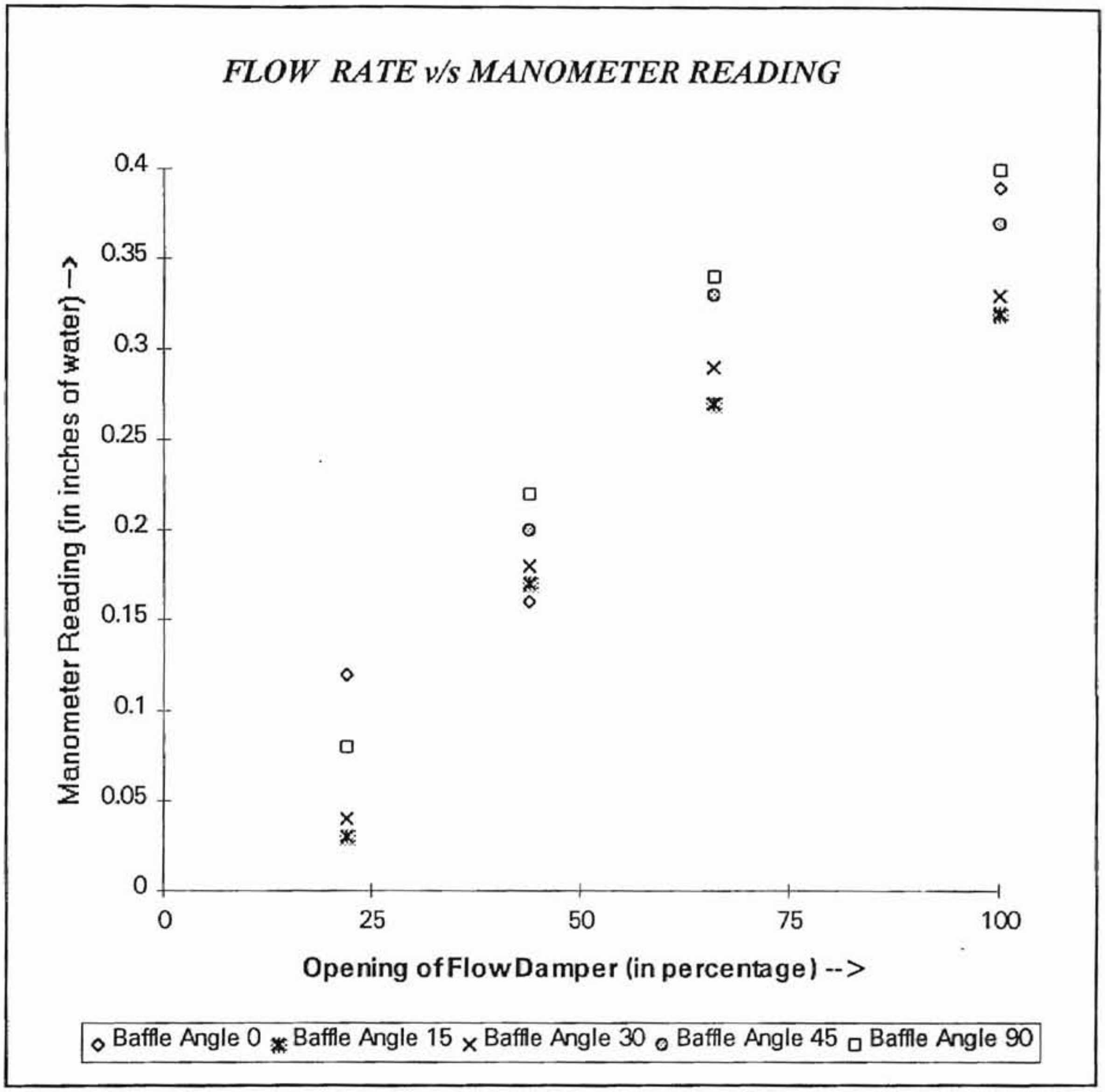


Fig. 26 Manometer Reading (Dynamic Pressure) for different flow rate and angle of baffle plate

From the above graph it can be seen that as the angle of the baffle is increased from 15 degrees to 90 degrees, the pitot tube reading (using a manometer) is also increasing in a uniform manner.

However, when the baffle angle is at 0 degree, one can see a abrupt increase in the pitot tube reading with the increase in opening of the flow damper.

• ***Flow rate v/s RMS amplitude***

The graph for this case is shown in the following page. The RMS amplitude of flutter velocity of the web increases rapidly and becomes unstable as the flow rate is increased by opening the flow damper. The magnitude at 88% opening of the flow is about 2400 mV (i.e. about 10 times the maximum velocity amplitude for the case with a baffle in the test section). So, it can be clearly seen that at a baffle angle of 30 degrees and above, the amplitude of velocity initially increases but after a particular point starts dropping down again even when the flow is further increased. Thus, initially, a curvature is caused in the web by inserting the baffle. And, when the baffle is above some critical angle, the web becomes more and more stable even if the flow rate is increased. Thus, the RMS amplitude of velocity decreases even if the flow rate is increased after a certain point. This is very significant as it shows that the method is not only effective in the suppression of flutter, but, becomes more effective with the increase in the flow. The dotted lines as shown in the graph were made to show the approximate trend of the RMS amplitude with the increase in flow for various angles. While plotting, the data for 0 degree angle of baffle plate is deliberately removed because the magnitude of velocity in this case is so high that the plot cannot be shown all together in one place.

FLOW RATE v/s RMS AMPLITUDE

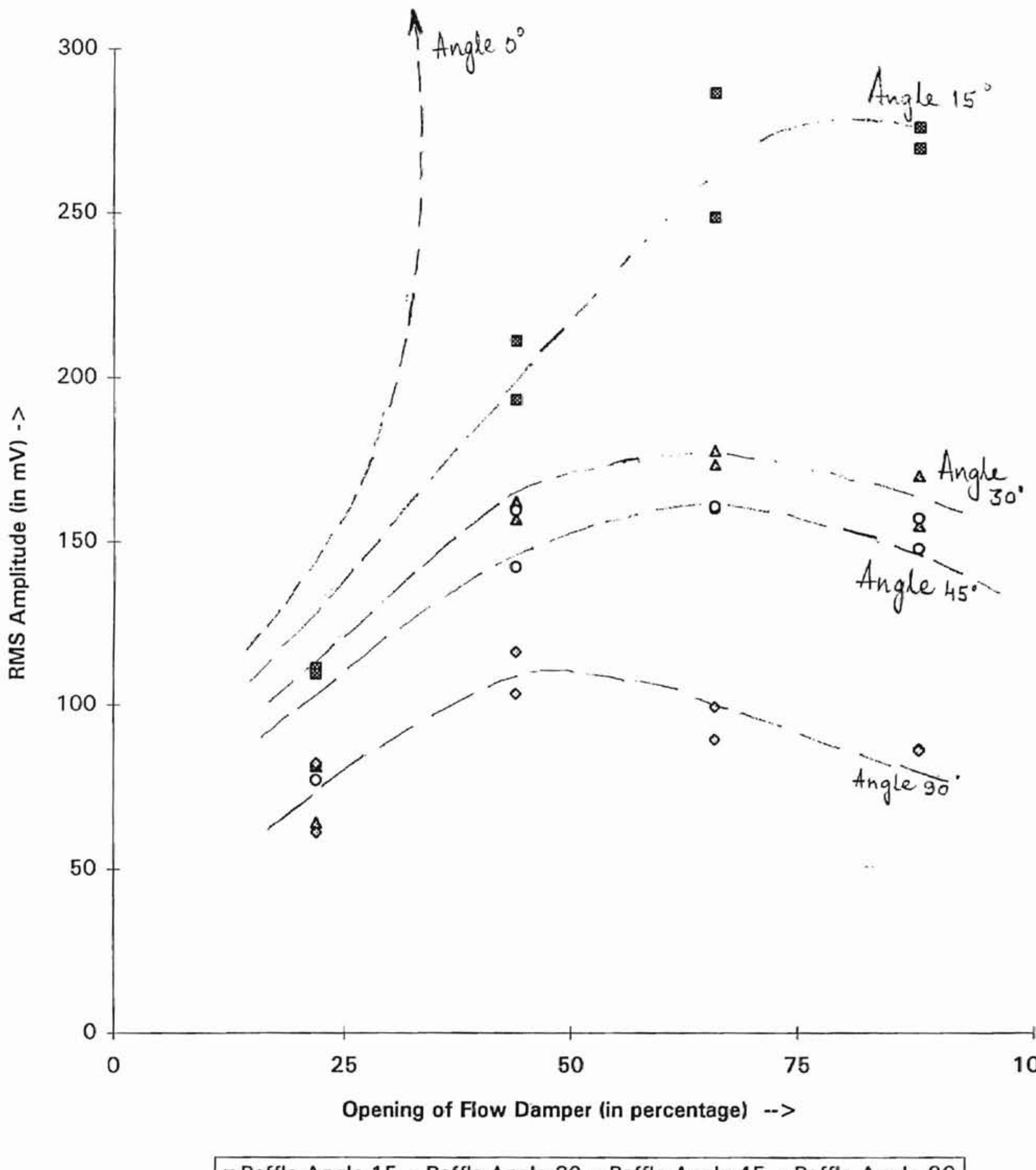


Fig. 27 RMS Amplitude of flutter velocity with change in flow rate
(1000 mV = 125 mm/s. Dotted line shows the approximate trend. Data for 0 deg. angle is not shown as its value is very high comparatively.)

VI. Effect of the change in height of the baffle plate in controlling flutter.

These set of test was conducted to see how the size of the blockage effects web flutter.

- *Height of the baffle v/s Manometer Reading.*

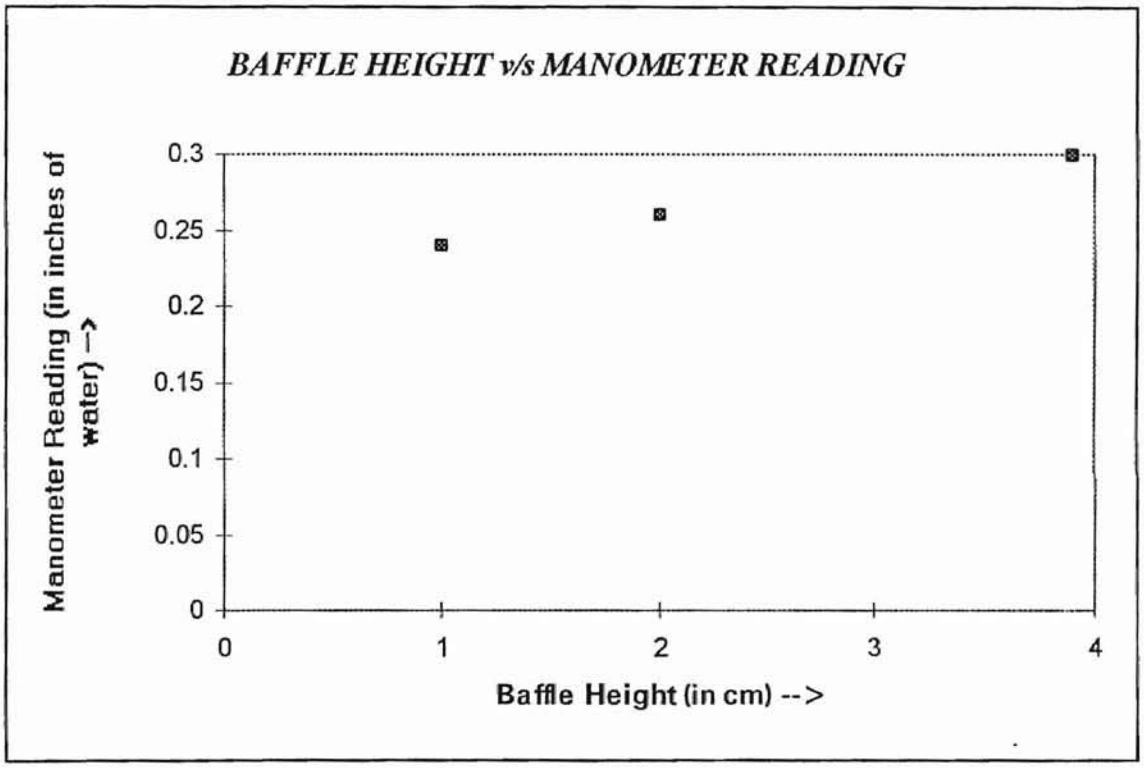


Fig. 28 Manometer reading (Dynamic Pressure) for variation in baffle height

As seen from the above graph the pitot tube reading increases as the baffle height is increased. This is because as the baffle height increase more and more air is deflected towards the web and therefore there is a rise in the manometer reading.

• *Baffle Height v/s RMS Amplitude*

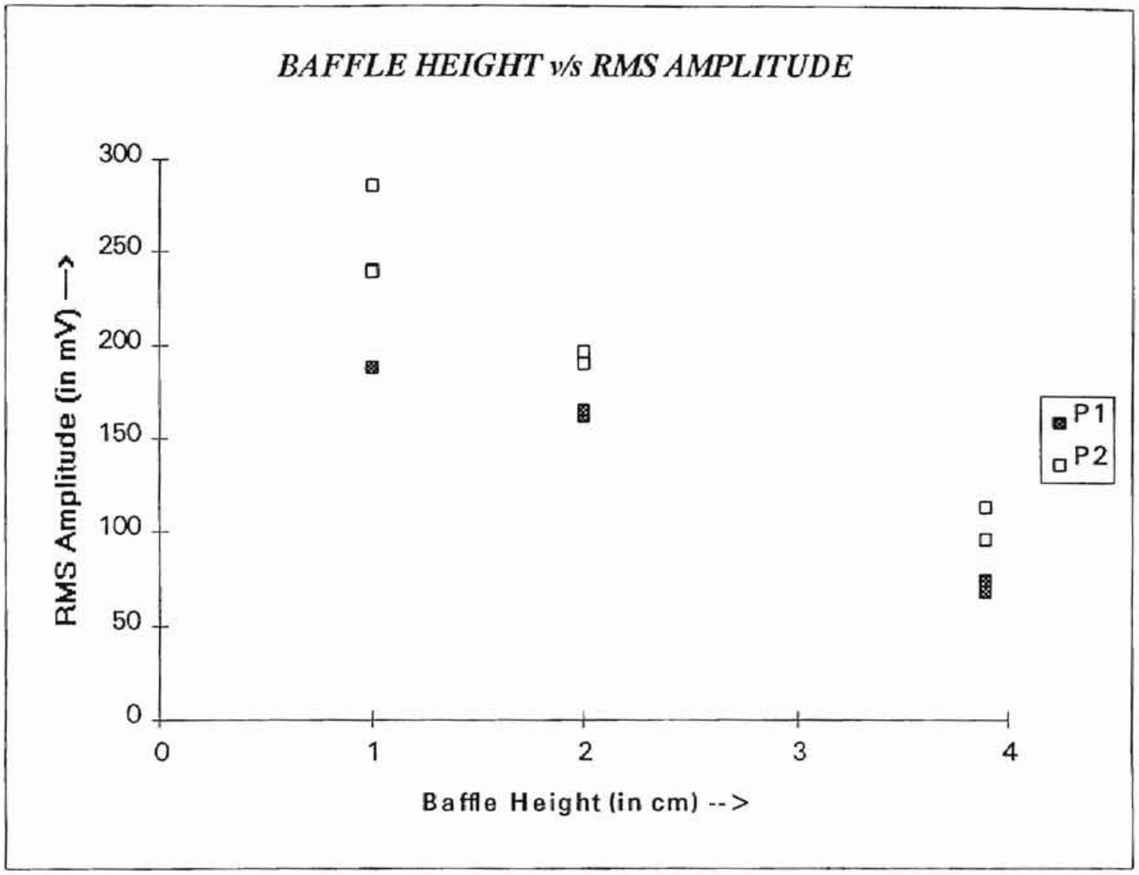


Fig. 29 RMS Amplitude of flutter velocity for variation in baffle height
(1000 mV = 125 mm/s)

As seen from the above graph even a baffle of height 1 cm is enough to drop the flutter amplitude substantially. Note that the RMS amplitude without the baffle plate (or baffle at an angle of 0 deg.) is about 2500 mV.

VII. Effect of change in tension on Web Flutter.

These tests were conducted to observe the validity of the baffle plate when the web is very slack or under high tension. The general observation was that as the web was made very slack the baffle plate was able to produce a high curvature in the web and thus control flutter. As can be seen in the following graph there is a small rise in flutter even when the web was under almost no tension.

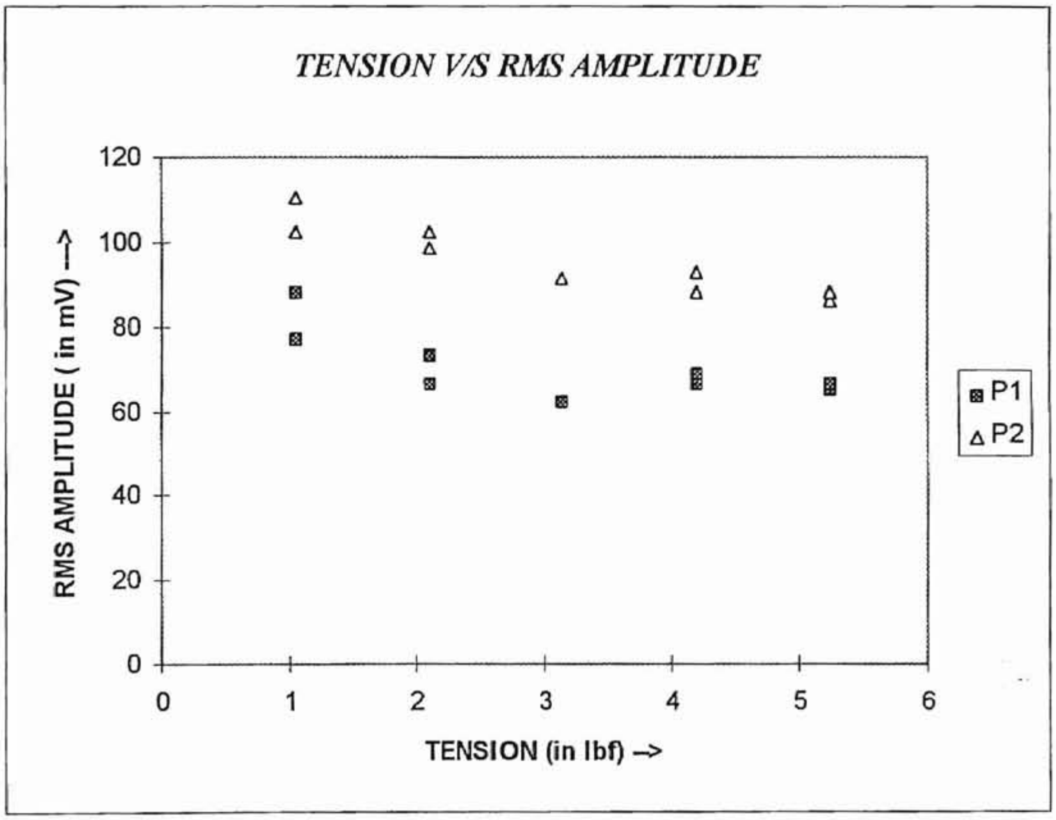


Fig. 30 . RMS amplitude of flutter velocity for different web tension.
(1000mV = 125 mm/s)

VIII. Estimation of the induced tension in the slack downwind edge of the web.

The underlying principle for this technique of flutter suppression is the tension induced in the downwind (slack) edge of the web. This induced tension is caused due to an asymmetry in the flow path. Due to this asymmetry, the flow patterns are changed and thus the downwind edge has a curvature due to the difference in static pressure above and below the web.

To estimate the induced tension, it is required to measure the curvature and static pressure difference, along the downwind edge of the web. Similarly, curvature can be determined by measuring the deflection at the downwind edge.

Static pressure measurement was done by traversing a pitot-static tube along the downwind edge (Figure 31). In the pitot-static tube measurements, the open tube was facing the flow. The fine holes around the periphery of the closed tube were close to the downwind edge. However, no traversing mechanism was designed to move the pitot-tube along the downwind edge.

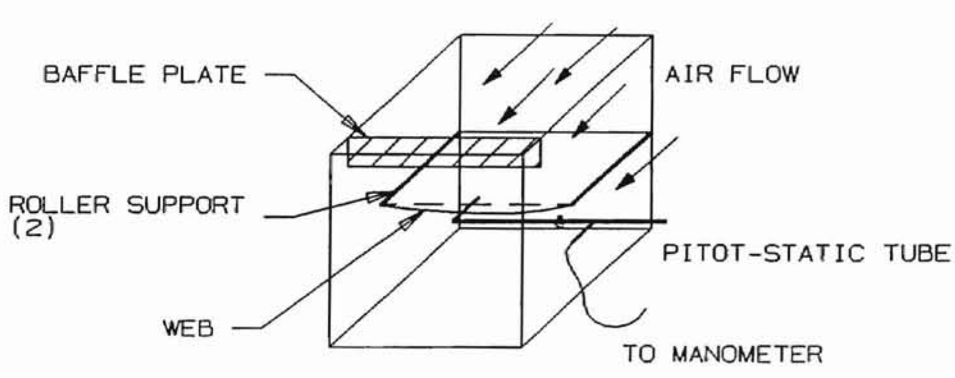


Fig. 31 Static pressure measurement

The deflection of the web with a baffle plate was measured by using a filar telescope. Since the downwind edge appeared to be fuzzy, due to flutter, the laser beam of the laser-Doppler sensor was used in aiding measurement with filar telescope. The laser beam was incident at the downwind edge and then the filar telescope was focused on that beam rather than the fuzzy downwind edge.

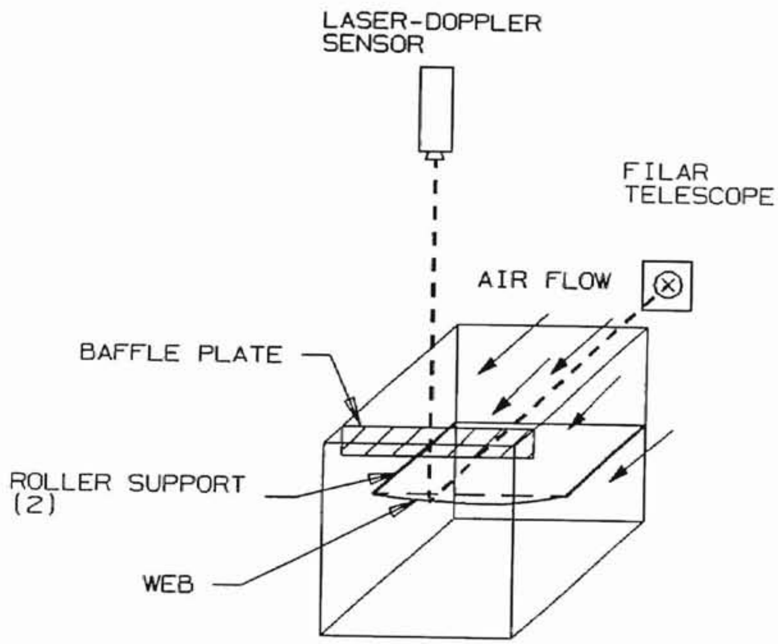


Fig. 32 Measurement of deflection of the web

After measuring the deflection at 12 equidistant points (1" apart), along the web, curve-fitting was done to remove the discontinuities. The radius of curvature R is found using the equation:-

$$R = \frac{[1+(y')^2]^{3/2}}{y''}$$

where y' = f' (x) first derivative of f(x) at a point (tangent to the curve at that point)

y'' = f'' (x) second derivative of f(x) at the same point.

The basic equation used for measuring the induced tension is:-

$$\Delta P = T \text{x} \frac{\partial^2 y}{\partial^2 x}$$

$$where \frac{\partial^2 y}{\partial^2 x} = \frac{1}{\text{R}} \qquad .....(\text{I})$$

R is the radius of curvature and T is the induced tension per unit width of the web.

The following table shows the properties of the webs being tested in all experiments for this study:-

Table 2

Material properties of tested webs

Material	Plastic 1	Modulus of Elasticity (Ey)	4440 MPa
Height (h)	38 μm	Flextural Rigidity of Web (Dx)	1.00 E-05
Mass (m)	0.0276 kg/m^2	Flextural Rigidity of Web (Dy)	17.4 E-06
Modulus of Elasticity (Ex)	1980 Mpa	Modulus of Rigidity (G)	1880 MPa

The computed values for the induced tension varied by about 30% from its minimum value. The minimum value of the induced tension on the web was used for analysis. Chang [27] made a simplified analysis of stability of a web with a freewind edge based on potential flow theory. The stability equation is given by

$$\frac{qL^3}{D} = \frac{\pi^3}{2}(M_R + \sqrt[4]{T_R})(1 + \sqrt{T_R}) \qquad .....(\text{II})$$

where

$$q = \text{Dynamic Pressure} = \frac{\rho v^2}{2}$$

$$L = \text{Web Span (Cross - flow Direction)}$$

$$D = \text{Bending Stiffness of Web} = \mathrm{E\,t}^{3} / 12(1-\nu^{2})$$

$$M_R = \text{Mass Ratio} = \frac{2\,\rho\,l}{\pi\,m}$$

$$T_R = \text{Tension - stiffness Ratio} = \frac{T\,l^2}{\pi^2\,D}$$

The left hand side of the stability equation (II) represents the flow parameter whereas the right hand side is shown as the tension parameter.

As shown in Table 3, the flow parameter and the tension parameter was computed by considering the minimum value of induced tension estimated by equation (I).

Table 3

Induced Tension and Stability Parameters

Flow Velocity (fpm)	Curvature at Center (m)	Static Pressure Difference (N/m^2)	Induced Tension (N/m)	Flow Parameter	Tension Parameter
2200	1.055	7.5	7.91	2.1 E+05	8.5 E+04
2700	0.86	10.6	9.12	3.22 E+05	1.1 E+05

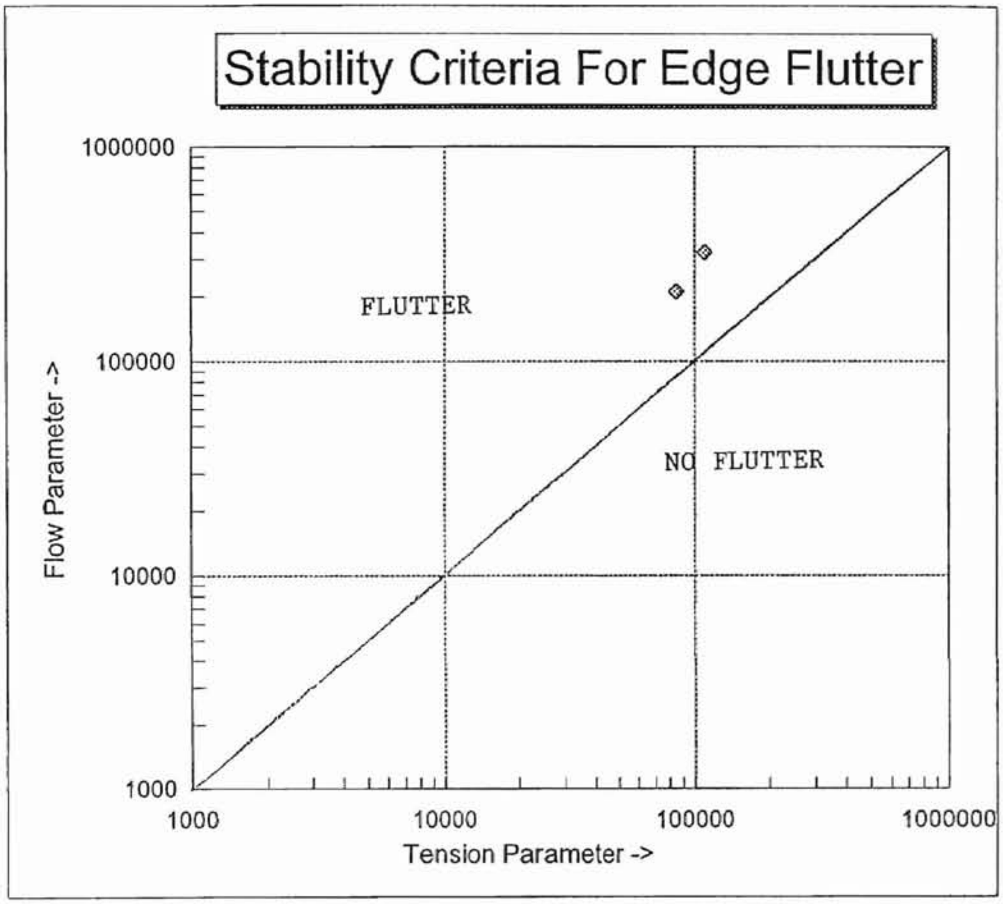


Fig. 33 Stability criteria for edge flutter [3]

Thus, because of the curvature and hence the induced tension we are almost in the stable region where their is no flutter. Additional stiffening may be ascribed to curving the web into a cylindrical or conical shell due to presence of the baffle plate. This will result in the web being in a stable region.

All the data taken in this case were approximate; the tension found by this method was found to vary by almost 30%. When the flow rate was increased the rise in the tension parameter was also proportional. This again validates the point which earlier experiments proved that this technique works for over a range of flow rates.

CHAPTER V

CONCLUSIONS AND SUGGESTIONS FOR FURTHER WORK

Conclusions

A new technique for suppressing edge flutter in a slack edge was tried and various tests were performed to check its effectiveness with varying conditions. From the study the following conclusions were obtained :

1. Web flutter is suppressed when we modify the flow patterns by putting a blockage to the flow field, such as a simple plate structure. This causes a curvature at the slack downwind edge and thus a tension is induced in it.

2. The region close to the downwind free edge or beyond is the place where a baffle plate suppresses web flutter most effectively.

3. When the angle of the baffle is changed near the downwind free edge there is a significant change in flutter amplitude. The baffle suppresses flutter if the angle is 90 degrees or below. However, when the angle is increased beyond 90 degrees there is an increase in flutter amplitude.

4. Flow visualization test by the Tufts method suggest that the baffle acts to deflect the flow and induce a curvature in the web.

5. Contrary to the symmetrical flow, with a baffle, increase in the flow rate seems to make the web more and more stable.

6. Putting a baffle plate to block 8 per cent of the cross-sectional area also seems to suppress web flutter substantially.

7. Approximate measurement of the induced tension at the downwind edge and comparison with the stability criteria as developed by Chang shows that induced tension due to the presence of an asymmetry in the form of baffle plate brings the web into the stable (non-flutter) region. An increase of flow rate shows an increase in the induced tension, so that increased flow excitation is accompanied by increased pressure stabilization.

8. Additional stiffening may be ascribed to curving the web into a cylindrical or conical shell.

Suggestions for further study

1. Air flow arrangements which slightly increase the pressure on one side of the web should be developed for web handling applications.

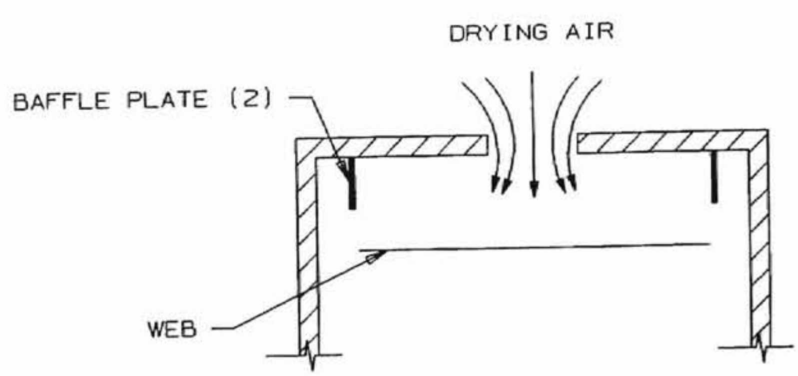


Fig. 34 Air flow arrangement for web-handling applications

2. Air jet technology should be investigated for suppressing flutter.

3. We need computational techniques to analyze the complicated flow fields and the complex motion of a web interacting with the surrounding air flow.

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