

Aug. 17, 1965

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3,201,305

SHEET FORMING METHOD AND APPARATUS

Filed Nov. 5, 1962

2 Sheets-Sheet 1

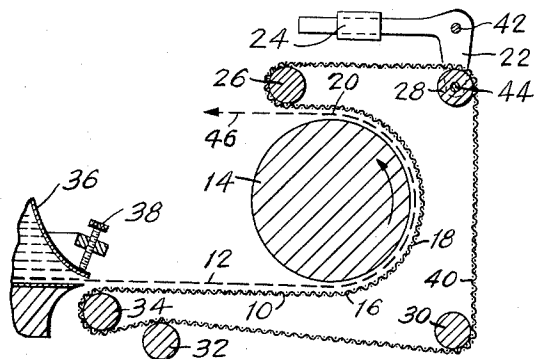


Fig. 1

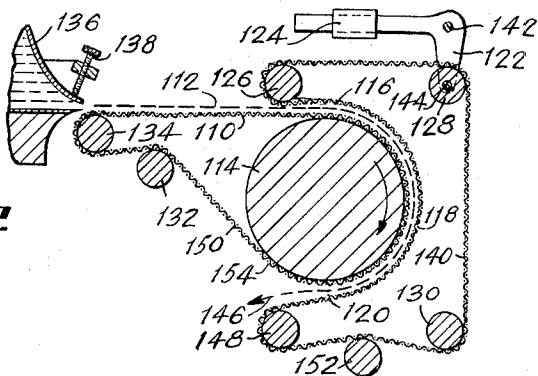


Fig. 2

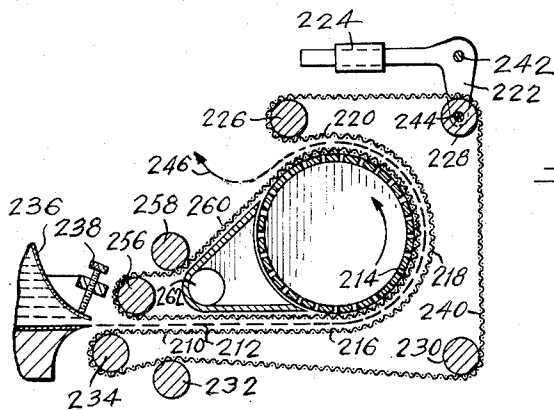


Fig. 3

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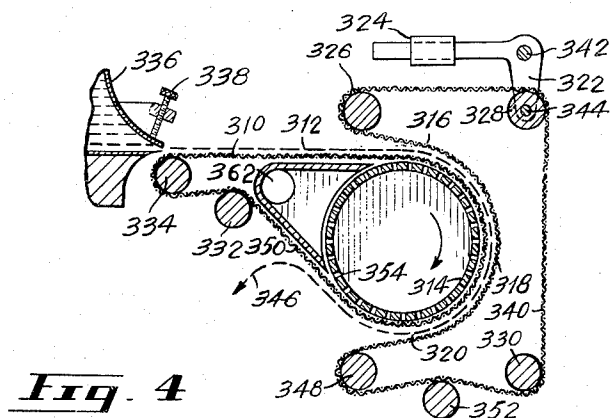
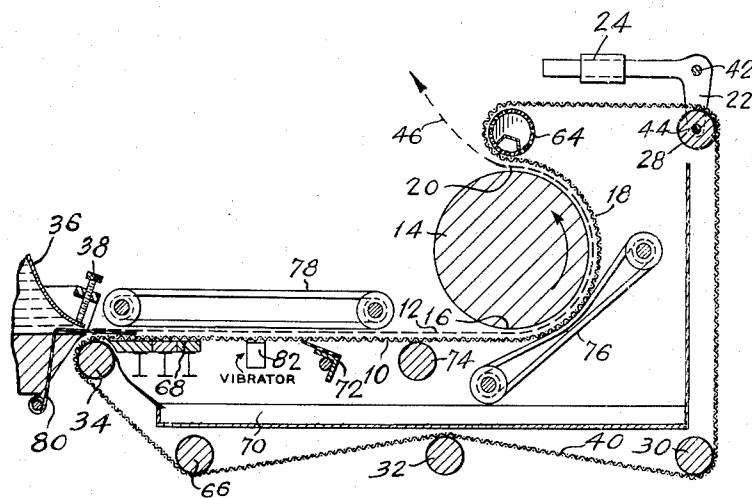
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2 Sheets-Sheet 2



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3,201,305
SHEET FORMING METHOD AND APPARATUS
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 Filed Nov. 5, 1962, Ser. No. 235,326
 10 Claims. (Cl. 162—203)

The present invention relates to sheet forming and more particularly to a method and apparatus for forming a continuous sheet of paper from fibres in liquid suspension.

Paper is made currently by either of two main processes, the cylinder machine, and Fourdrinier machine.

The cylinder machine has the main difficulties, firstly of the sheet tending to rinse off the cylinder because of immersion in a vat, and secondly of the sheet tending to peel off the cylinder before formation is complete because of centrifugal force. Thirdly, the differential pressure forcing drainage is weak, being limited to the difference in liquid level inside and outside the cylinder. These and other difficulties restrict the cylinder machine to relatively slow speeds and small capacity.

The Fourdrinier machine has the main difficulties, firstly of the mesh dragging across stationary suction boxes, which requires a strong pull on the mesh thereby causing an abrasive creep at the drive roll. The suction-box drag and the drive-roll creep abrade the mesh quickly to where it cannot withstand the strong pull. Mesh replacement therefore is frequent and costly.

Secondly, a further difficulty is that the table rolls of a Fourdrinier by their pumping action draw down the mesh after the crest of each roll, and let the mesh rebound with such force that the free surface of the liquid becomes fractured thus spoiling formation. A main result is that a Fourdrinier sheet is only $\frac{3}{4}$ as strong as a sheet made by ancient hand methods. This agitation or vibration caused by the table roll has not only kept down the quality of the machine-made product, but the table roll also has been discovered by widespread research to impose a practical speed limit on the Fourdrinier of approximately 2,500 ft./min.

A third difficulty is that a negligible amount of liquid is removed between table rolls, whereby the mesh between rolls is merely a conveyor, and thus the drainage process is halted for most of the space occupied by the Fourdrinier. These and other difficulties restrict the quality and quantity of product off a Fourdrinier.

The present invention is aimed to avoid the above mentioned difficulties of cylinder and Fourdrinier machines by departing from some of their basic actions and constructions. In avoiding these difficulties the present invention provides a method and means, which firstly improve the quality, and secondly the quantity of paper produced per unit width.

The improvement in paper quality is achieved mainly by eliminating liquid disturbances and controlling fibre vibration. The improvement in quantity is achieved mainly by intensifying the drainage process necessary in pulp and paper sheet formation.

The present invention is an improvement on my United States Patent 3,056,719, issued October 2, 1962, Continuous Web Forming Machine, the present invention being adapted to use existing headboxes delivering a horizontal jet, and to control flocculation and interlocking of fibres by a control of vibration.

More specifically, the method of the present invention comprises the steps of: delivering a substantially-horizontal and ribbon-like jet of fibres in liquid suspension to a substantially-horizontal mesh means; supporting said fibres on said mesh means; driving said horizontal-mesh means in the same direction as said jet; controlling said horizontal-mesh means according to the physical laws for a

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taut string, with regard to frequency, wave length, wave velocity, mesh tension, and mass per unit length, as a way to control fibre vibration; guiding said jet of fibres from said horizontal means directly around a vertical curve of substantial angle; draining said fibres in suspension around said vertical curve to leave a formed layer of fibres on said mesh means; and removing said layer of fibres from said vertical curve as a continuous self-supporting sheet.

The method of the invention may be carried out by a preferred apparatus which embodies in combination: a substantially-horizontal segment of an endless-mesh means adapted to travel with and support a ribbon-like layer of fibres in liquid suspension; carrying rolls for the mesh means including a drum mounted for rotation about a horizontal axis with the drum tangent to the horizontal segment of mesh; another segment of the mesh means comprising a loop wrapped around a substantial arc of said drum and adapted to guide the layer of fibres around the arc against centrifugal force; a first tension-control means including a carrying-roll portion with mounting means of the "floating" type cooperating with a tension regulator adapted to maintain a substantially-constant tension throughout the loop thereby providing a constant mesh-pressure against centrifugal force; during deflections of said mesh from drum by said layer of fibres; a second tension-control means including another carrying-roll portion with loading means adapted to set a magnitude of said constant tension, said magnitude of tension being for an optimum vibration of said horizontal segment of mesh as derived from physical laws for a vibrating string, said laws including the variables of frequency, wave length, wave velocity, mesh tension, and mass per unit length of mesh; whereby said apparatus includes control means for the amount of agitation of fibres in forming a sheet of paper.

Having thus generally described the nature of the invention, particular reference will be made to the accompanying drawings, and in which

FIGURE 1 is a somewhat diagrammatic showing in side elevation and partially in cross section of a preferred construction of an apparatus capable of carrying out the method of the invention with a plain drum, in which a horizontal segment of mesh, and an upward-curving segment of mesh are segments of a single endless mesh.

FIGURE 2 is a corresponding showing in side elevation and partially in cross section of an alternative construction with a plain drum, in which a horizontal segment of mesh, and a downward-curving segment of mesh are segments of two separate endless meshes.

FIGURE 3 is a corresponding showing in side elevation in cross section of an alternative construction with suction drum and box, in which a horizontal segment of mesh, and an upward-curving segment of mesh are segments of a single endless mesh. The suction drum and box are surrounded by a separate mesh to keep fibres from entering the drum.

FIGURE 4 is a side elevation in cross section of an alternative construction with suction drum and box, in which a horizontal segment of mesh and a downward-curving segment of mesh are segments of two separate endless meshes. The suction drum and box are surrounded by the same mesh which has the horizontal segment, and which also keeps the fibres from entering the drum.

FIGURE 5 is a side elevation in cross section of the preferred construction of FIGURE 1, with the optional equipment of adjustable forming board, drainage tray, doctor-blade damper, table-roll damper, drum deckle-belts, horizontal deckle-belts, vibrator, plus a suction-transfer roll and an extra mesh-carrying roll.

Referring more specifically to the drawings, in FIG-

FIGURE 1 is shown a preferred construction in which a layer 12 of fibres in liquid suspension is supported on a horizontal segment 10 of an endless mesh 40. The horizontal segment 10 is tangent to a plain drum 14 at an entry nip 16.

From tangency at entry nip 16, another segment 18 of mesh 40 is in tight wrap against drum 14, for a substantial arc to an exit nip 20. Mesh 40 is supported in tension as a free loop at drum 14 by an entry roll 34 and an exit roll 26, and in a return circuit by intermediate rolls 28, 30 and 32. A greater or lesser number of carrying rolls, and shape of mesh circuit, may be used as is found convenient.

The horizontal mesh-segment 10, the fibre in liquid suspension 12 and arcuate mesh-segment 18 all travel in unison throughout the wrap on drum 14 because mesh tension causes a frictional non-sliding contact between arcuate mesh-segment 18 and drum 14 through the medium of fibre layer 12 trapped between mesh and drum from entry nip 16 to exit nip 20. It is preferred to drive drum 14 by conventional drive means not shown. Alternatively, the drive may be applied by conventional drive means at any other roll or mesh part.

The fibre layer 12 is of ribbon-like shape as delivered by a headbox 36 of conventional form and utilizing conventional slice regulation 38. Take-up of the mesh 40, as the mesh stretches normally during its life is by conventional take-up means (not shown) at any convenient roll, for example at roll 30. Guiding also is by conventional guide means (not shown), for example at roll 32.

Tension-control means may be any of several conventional types, and in the preferred construction shown in FIGURE 1 has two portions, firstly a "floating" portion 22 which imparts a given thrust to roll 28, and secondly a loading portion 24 which determines the thrust at roll 28 and thus the tension in mesh 40. "Floating" portion 22 is secured to a paper-machine frame (not shown) by pivotal means 42, and to roll 28 by journal means 44, whereby roll 28 can deflect in a way to be described.

In some known types of tension regulator, the "floating" portion 22 for example might be replaced by piston-rod means, and the loading portion 24 might be replaced by a pneumatic or hydraulic means regulating pressure at the piston.

As another alternative, it is possible to use for example a non-moving pressure-sensitive support at roll 28, and to use conventional take-up means mentioned above for the "floating" function. Other alternative means of tension control will be apparent to those skilled in the art.

In operation, the mesh 40 directly touches drum 14 at startup, and the mesh is deflected from the drum by the fibre layer 12 forcing its way into entry nip 16. Fibre layer 12 thereby separates mesh from drum throughout arcuate mesh-segment 18 and is squeezed by tension in mesh 40 causing a radial pressure of mesh toward drum throughout arc 18.

The fibre layer 12 thereby has drainage expressed through the mesh, while the fibres are felted together, and the fibres then emerge at exit nip 20 as a self-supporting and continuous sheet 46 to be treated further in a conventional way. The drainage is re-cycled in a conventional manner.

The arcuate mesh-segment 18 is provided as a tensioned loop free to conform to any deflection or rate-of-taper of mesh from drum during the decrease of thickness of fibre layer 12 by drainage in advancing along arc 18. This feature of mesh-segment 18 being free flexing derives firstly from the elimination of a vat wall, and thus of fixed taper as found in cylinder machines, and secondly from the provision of a "floating" roll 28.

The "floating" roll 28 permits having a constant tension in mesh 40, and thus a constant mesh pressure against the drum in the forming zone throughout arc 18, regardless how far the fibre layer 12 may deflect the mesh from

drum. The initial deflection at entry nip 16 depends on variables, such as the layer thickness at slice 38, and the kinetic energy of fibre layer 12.

The rate-of-taper around mesh arc 18 depends as mentioned on rate-of-drainage. It is well known that fibres in liquid suspension drain at varying rates depending on variables such as quality of raw materials, fibre size, proportion of fines, liquid surface tension, and additives. This seepage of liquid is according to the laws of filtration. Thus, the rate-of-drainage depends also on pressure and time.

Pressure from mesh tension has been shown to be made virtually constant via "floating" roll 28 although there is some fluctuation from most controllers. Also there is a change in hydrostatic pressure from any difference in elevation between entry nip 16 and exit nip 20. Concerning time, the period to traverse arc 18 depends on machine speed, and thus the uniformity of traverse time depends on uniformity from the paper-machine speed controller.

A main advantage of having a free-flexing arcuate mesh-segment 18 is that the mesh can conform exactly to the decreasing thickness of the fibre layer 12, including conforming instantly to variations in rate-of-taper of that thickness, whereby the present invention keeps the entire thickness of the fibre layer 12 at a fixed speed and thereby prevents having liquid-shear planes harmful to formation.

An experimental paper machine has made paper both without a "floating" roll, and with the "floating" roll fixed in one position, and the lack of this "floating" feature left a partial lack of control over controlling machine operation and paper quality. Thus the "floating" feature of roll 28 is a means of helping to control sheet quality.

The magnitude of mesh tension, determined by loading means 24, also determines the unit pressure at arc 18 and thereby the drainage rate. The stronger the pressure the faster the drainage rate.

The magnitude of mesh tension also determines the manner in which fibre layer 12 enters nip 16. For example, the kinetic energy of fibre layer 12 would normally be strong enough to force its way into entry nip 16, but if loading means 24 increases mesh pressure substantially, then a limit is reached where kinetic energy of fibre layer 12 is insufficient to deflect mesh 10 enough to admit all stock into entry nip 16. Some stock then is rejected at the nip as an overflow. Up to this limit, the greater the pressure the greater the drainage capacity.

Means to control the magnitude of mesh tension therefore provide a means of helping to increase drainage rate and thereby to increase the machine speed and the quantity of sheet produced.

Simultaneously with setting the magnitude of mesh tension for drainage rate, this same tension also helps to determine the natural frequency of horizontal mesh-segment 10 according to the law for standing waves

$$V = \sqrt{\frac{T}{M}}$$

to be described. The effect of mass will also be explained.

A main advantage of such vibration is to prevent fibre flocculation, and to interlock the fibres for sheet strength. Also the span of horizontal mesh-segment 10 is so short compared to the length of a Fourdrinier, that the vibrations are small and mild compared to the violent impulses at table rolls.

The combination of parts in the present invention thus provides a method and means for improving paper quality, by eliminating liquid disturbances and controlling fibre agitation, and for improving paper quantity by intensifying the drainage action.

In FIGURE 2 is shown an alternative construction in which the vibration and pressure controls are effected

through two separate endless meshes. A layer 112 of fibres in liquid suspension is supported on a horizontal segment 110 of an endless mesh 150. The mesh segment 110 is tangent to a plain drum 114 at a point 116.

From tangency at point 116 mesh 150 is in tight wrap against drum 114 for a substantial arc to an exit point 154. Mesh 150 is supported in a return circuit at any number of rolls such as roll 132 and breast roll 134. At least one roll, such as roll 132 is fitted with conventional guide and tension-control means (not shown). Tension in mesh 150 is adjusted by such tension control means to control the horizontal mesh-segment 110 according to the physical laws for standing waves.

Another endless mesh 140 has an arcuate segment 118 in tight wrap overlying the mesh 150 from tangent point 116 to an exit point 120. The overlying mesh 140 can have a lesser arc on driving drum 114 than mesh 150 if desired. Mesh 140 is supported as a free loop in tension at drum 114 by an entry roll 126 and an exit roll 148, and in a return circuit by intermediate rolls 128, 130 and 152. A greater or lesser number of carrying rolls, and a variance in shape of mesh circuit, may be used as is found convenient.

The horizontal mesh-segment 110, the fibre in liquid suspension 112, and the arcuate mesh-segment 118 all travel in unison throughout the wrap on drum 114 by frictional non-sliding contact with one another. The layer of fibres in liquid suspension 112 makes its own way, by deflecting arcuate mesh-segment 118 from drum 114, while mesh 150 remains tightly against the drum 114.

Fibre layer 112 thereby is squeezed between meshes 140 and 150, throughout arc 118 from entry 116 to exit 120, by mesh 140 being tensioned to create a radial pressure toward drum 114.

Takeup of the mesh 140, as the mesh stretches normally during its life, is by conventional takeup means (not shown) at any convenient roll. Guiding also of mesh 140 is by conventional guide means (not shown) as at roll 152.

Tension control is by any conventional means for example firstly by a "floating" portion 122, secured to the paper machine frame by pivot 142 and to roll 128 by shaft 144, and secondly a loading portion 124. The "floating" portion 122 accommodates various mesh deflections instantly, thereby to maintain constant tension, and the loading portion 124 sets the magnitude of the constant tension as previously described for FIGURE 1.

The fibre layer 112 is of ribbon-like shape as delivered by any headbox 136 and conventional slice regulation 138. Drainage is expressed through mesh 140 while the fibres are felted together and emerge at exit 120 as a self-supporting and continuous sheet 146.

Operation is similar to the operation per FIGURE 1 except that control of horizontal mesh-segment 110 is operated separately from the rate-of-drainage control by tension in mesh 140. As previously described, vibration control is to prevent fibre flocculation, and to interlock fibres for sheet strength in a way not possible at high speed with cylinder and Fourdrinier machines.

In FIGURE 3 is shown an alternative construction in which the plain drum of FIGURE 1 is replaced by a suction drum. A layer 212 of fibres in liquid suspension is supported on a horizontal segment 210 of an endless mesh 240. The mesh segment 210 is tangent to a suction drum 214 at an entry nip 216.

From tangency at entry nip 216, another segment 218 of mesh 240 is in tight wrap toward drum 214 for a substantial arc to an exit nip 220. Mesh 240 is supported in tension as a free loop at drum 214 by an entry roll 234 and an exit roll 226, and in a return circuit by intermediate rolls 228, 230 and 232. A greater or lesser number of carrying rolls, and shape of mesh circuit, may be used as is found convenient.

Another endless mesh 260 also is in tight wrap about

the same substantial arc as segment 218, and more, and mesh 260 lies between the periphery of suction drum 214 and mesh 240. Endless mesh 260 has a return circuit supported by any number of rolls, for example roll 256 and roll 258, and mesh 260 encircles a suction box 262 which transmits suction throughout arcuate segment 218.

This suction roll 214, with suction box 262, rolls 256 and 258, mesh 260, and headbox 236-238 is in accordance with my United States Patent 3,057,402, issued October 9, 1962, Silent Suction Roll. Other types of porous roll using vacuum or pressure may be used from known art.

Takeup of mesh 240, as the mesh stretches normally during its life, is by conventional takeup (not shown) at any convenient roll for example roll 230. Guiding also is by conventional guide means (not shown) for example at roll 232.

Tension control is by any conventional means for example firstly by a "floating" portion 222, secured to paper-machine frame by pivot 242 and to roll 228 by shaft 244, and secondly by a loading portion 224. The "floating" portion 222 accommodates various mesh deflections instantly, thereby maintaining constant tension, and the loading portion 224 sets the magnitude of the constant tension as described for FIGURE 1.

The horizontal mesh-segment 210, the fibre in liquid suspension 212, and the arcuate mesh-segment 218 all travel in unison throughout the wrap on drum 214 by frictional non-sliding contact with one another.

Fibre layer 212 is of ribbon-like shape as delivered by any headbox 236 and conventional slice regulation 238. Drainage is expressed through mesh 240, and simultaneously through mesh 260, at arcuate segment 218 while the fibres are felted together and emerge at exit 220 as a self-supporting and continuous sheet 246.

As in FIGURE 2, fibre layer 212 makes its own way between meshes 240 and 260 from entry 216 to exit 220, whereby mesh 240 is deflected as a free loop, and mesh 260 remains in tight contact with drum 214.

Operation is similar to the operation per FIGURE 1, except that drainage is reclaimed from two sources instead of one, namely drainage issues away from drum 214 through mesh 240 at arcuate segment 218, and drainage issues into drum 214 through mesh 260 at arcuate segment 218. Drainage from the two sources is recycled in a conventional way.

As previously described, the vibration control is to prevent fibre flocculation and to interlock the fibres for sheet strength in a way not possible at high speed with cylinder machines and Fourdriniers.

In FIGURE 4 is shown an alternative construction in which the vibration and pressure controls are effected through two separate endless meshes. A layer 312 of fibres in liquid suspension is supported on a horizontal segment 310 of an endless mesh 350. The mesh segment 310 is tangent to a suction drum 314 at point 316.

From tangency at point 316, mesh 350 is in tight wrap against drum 314, for a substantial arc to an exit point 354. Mesh 350 is supported in a return circuit at any number of rolls such as roll 332 and breast roll 334. At least one roll, such as roll 332 is fitted with conventional guide and tension-control means (not shown). Tension in mesh 350 is adjusted by such means in order to control the horizontal mesh segment 310 according to the physical laws for standing waves as described for FIGURE 2.

Another endless mesh 340 has an arcuate segment 318 in tight wrap overlying mesh 350 from tangent point 316 to an exit point 320. The overlying mesh 340 can have a lesser arc on drum 314 than mesh 350 if desired. Mesh 340 is supported as a free loop in tension at drum 314 by an entry roll 326 and an exit roll 348, and in a return circuit by intermediate rolls 328, 330 and 352. A greater or lesser number of carrying rolls,

and shape of mesh circuit, may be used as is found convenient.

Mesh 350 also circuits around a suction box 362 which transmits suction to fibre layer 312 from entry 316 to exit 354 in accordance with my United States Patent 3,057,402, issued October 9, 1962, Silent Suction Roll.

The horizontal mesh-segment 310, the fibre in liquid suspension 312, and the arcuate mesh-segment 318 all travel in unison throughout the wrap on drum 314 by frictional non-sliding contact with one another. The layer of fibres in liquid suspension 312 make their own way, by deflecting arcuate mesh-segment 318 from drum 314 while mesh 350 remains tightly against drum 314 as for FIGURE 2.

Fibre layer 312 thereby is squeezed between meshes 340 and 350 from entry 316 to exit 320, and simultaneously is drained by suction from entry 316 to exit 354.

Takeup of the mesh 340, as the mesh stretches normally during its life, is by conventional takeup means (not shown) at any convenient roll. Guiding also of mesh 340 is by conventional guide means (not shown) as at roll 352.

Tension control is by any conventional means for example firstly by a "floating" portion 322 secured to paper-machine frame by pivot 342 and to roll 328 by shaft 344, and secondly a loading portion 324. The "floating" portion 322 accommodates varying mesh deflections instantly, thereby maintaining constant tension, and the loading portion 324 sets the magnitude of the constant tension as described in FIGURE 1.

The fibre layer 312 is of ribbon-like shape as delivered by any headbox 336 and conventional slice regulation 338. Drainage is expressed through mesh 340 at arcuate segment 318, and simultaneously through mesh 350, while the fibres are felted together and emerge at exit 354 as a self-supporting continuous sheet 346.

Operation is similar to operation per FIGURE 1 except that drainage is recovered from two sources instead of one, namely the drainage issues per FIGURE 3 away from drum 314 through mesh 340 at arcuate segment 318, and drainage issues into drum 314 through mesh 350 at arcuate segment 318. Drainage from the two sources is re-cycled in a conventional way.

As previously described, the vibration control is to prevent fibre flocculation and to interlock the fibres for sheet strength in a way not possible at high speed with cylinder machines and Fourdriniers.

Suction box 362 can be used for damping vibrations by raising it slightly against horizontal mesh-segment 310, in the nature of a forming board.

In FIGURE 5 is shown the preferred construction of FIGURE 1 in which are added: the optional structures of adjustable forming-board 68, drainage tray 70, doctor-blade damper 72, table-roll damper 74, drum deckle-belt 76, horizontal deckle-belt 78, adjustable apron 80, and vibrator 82. Although deckles 76 and 78 are shown with a gap between them, they can be extended toward each other to effect a more complete seal at the mesh edges.

Also in FIGURE 5, the exit roll 26 is replaced by optional suction-transfer roll 64. An extra mesh-carrying roll 66 helps to provide room for tray 70. Any, or all these optional structures may be used, as desired. Other conventional accessories for Fourdriniers may be added if desired. All these optional parts are fitted to the paper-machine frame (not shown) by adjustable means well known in the art.

In operation, the suction roll 64, the carrying roll 66, the tray 70 and the deckles 76 and 78 operate in a conventional way also well known in the art. The adjustable forming-board 68, the adjustable-doctor damper 72, the adjustable-roll damper 74, adjustable apron 80, and vibrator 82 are each adjusted to control vibration of horizontal mesh-segment 10 as described in an example fol-

lowing to provide vibration control, thereby to prevent fibre flocculation and to interlock the fibres for sheet strength in a way not possible at high speed with known methods and means.

The method for adjusting mesh tension, mass per unit length, wave length, frequency and wave velocity by these structures will be described.

In order that the basic concept of the present invention may be more clearly understood, reference will be made to the following theory and example.

Theory

In the apparatus of the present invention the use of a substantially-horizontal segment of an endless mesh-means, adapted for vibration control, according to the physical laws for standing waves is based on the following theoretical considerations.

It is well known that a transverse wave travelling in a string may be analyzed by visualizing a string, with a tension T and mass per unit length M , being pulled rapidly at velocity V through a glass tube having the shape of any curve for example one phase of a sine curve. At any point where the radius-of-curvature of the tube is R , the pressure against the tube or force per unit length is

$$\frac{T}{R}$$

being greater the sharper the curve.

Considering a unit length of the string, it is travelling in a circular path and must be subject to a centripetal force

$$F = \frac{MV^2}{R}$$

Now the forces of tension acting tangentially at the two ends of the unit length are not quite in line with each other. Thus we have a small force-vector acting on the unit length toward the centre-of-curvature.

If the string speed is right, this force vector from string tension will be just sufficient to supply the centripetal force without any help from the glass tube, and then

$$\frac{MV^2}{R} = \frac{T}{R}$$

That is $MV^2 = T$.

Since the radius-of-curvature cancels out of the result, the speed at which pressure vanishes against the tube is the same whatever the radius-of-curvature may be, and thus whatever the string shape. That is, for a given mass and tension, there is a Critical Speed at which the inward and outward forces exactly balance.

If the string is pulled through at this Critical Speed, the glass tube may be made to vanish, and the bend in the string will remain unchanged. If the observer now moves along at this Critical Speed from left-to-right, the string will appear stationary and the bend will appear to travel right-to-left with a velocity V , where

$$V = \sqrt{\frac{T}{M}} \quad \text{Formula (1)}$$

This is a well known law for vibration of a string.

In papermaking, a mesh is pulled along and the above analysis indicates that there is a Critical Speed of pulling at which the mesh can retain bends of any radius without external support from such as table rolls. An example of such standing waves is seen sometimes in the slack return-run of variable speed power-transmission belts.

Another well known law for vibration of a string,

where the wave travels at a velocity V and has wave length L and has frequency N is:

$$V = NL \quad \text{Formula (2)}$$

When waves reflect from the end of a string opposite their source, the interaction of similar trains of waves running in opposite direction causes the string to have standing waves with nodes and loops at fixed intervals. The distance between consecutive nodes is $\frac{1}{2}$ wave length.

Equating wave velocity of the above two formulas we have:

$$\sqrt{\frac{T}{M}} = NL$$

That is

$$N = \frac{1}{L} \sqrt{\frac{T}{M}} \quad \text{Formula (3)}$$

Below are three well known laws for a string based on this third formula and useful in operating the present invention.

(a) The number of vibrations per second made by a string under a given tension and mass per unit length is inversely proportional to the length of the vibrating segment. Thus if we half the length of segment, by damping it in the middle, we double the vibrations per second.

(b) The number of vibrations per second made by a string of a given length and mass per unit length is proportional to the square root of the tension. Thus if we quadruple the tension we double the vibrations per second.

(c) The number of vibrations per second made by a string of given length and tension is inversely proportional to the square root of the mass per unit length. Thus if we quadruple the mass per unit length we half the vibrations per second.

With a Fourdrinier the table-roll pumping action flexes the mesh into the shape of a crest at each table roll and a sump between rolls. This fixes the number of vibrations to the number of table rolls.

Compared to a wave, such crests would correspond to loops and such sumps to loops with a node between each crest and sump. Thus, there would be two nodes between adjacent table rolls and one wave length would be the centre-to-centre distance between rolls. As such table-roll loops are not free to vibrate vertically, but are of fixed curvature, a Fourdrinier mesh may be compared to the preceding analysis using the analogy of a string being pulled through a glass tube.

But a Fourdrinier is operated without regard to any Critical Speed of wave at which mesh tension is just sufficient to supply the centripetal force. At such Critical Speed, a table roll for example could be made to vanish and the mesh would retain its table-roll loop unchanged, except for two practical considerations.

Firstly, removing a table roll would remove its pumping action and thereby would cause a mesh movement to a new equilibrium of forces. Secondly, liquid resting on the mesh comprises a major part of the mass per unit length and does not withstand tension except for a small contribution from liquid surface tension. This weakness in tension contributes for example to liquid escaping from the loop over table rolls in the familiar pattern of "jumping," and in addition to loop curvature the "jumping" is aggravated by some drainage rimming the table roll and striking the mesh from underneath. Also the mesh vibrates more as a ribbon than as a string.

However, the instant invention introduces a way to eliminate the fixed pattern of vibrations at table rolls by introducing pressure drainage so strong around a vertical curve that table rolls are not needed for drainage. Also means are introduced for controlling vibration of the horizontal segment of mesh with adjustment to com-

promise between a big enough vibration to prevent flocculation of fibres and a small enough vibration to prevent damaging paper strength.

In accordance with the present invention the slower a layer of fibres traverses the horizontal segment of mesh the longer a time it is vibrated and thus the more times a fibre is vibrated. Therefore, one way to minimize the number of fibre agitations in the present invention is to speed the jet as much as possible. In contrast any speeding of a Fourdrinier increases the fibre agitations,

Upon reaching the Critical Speed where the mesh speed equals wave speed, and assuming that jet and mesh act together as a single mass for the present amplitudes, each fibre rides a "frozen" series of loops and follows in the same path as every preceding fibre.

The present invention therefore introduces a paper-making method and apparatus which controls vibration pattern, independently of table rolls, by control means for frequency, wave length, wave velocity, mesh tension and mass per unit length of mesh. More specifically, these separate but interrelated control methods and means are as follows.

Control of frequency

Above are given three laws, based on Formula 3, for the effects on frequency from a change in any of the factors of wave length, tension, and mass. The resultant frequency is for a free vibration.

But we may also impress a forced vibration on a string is desired. If such forced frequency corresponds to the free or natural frequency, then a strong resonance results with great amplitude. But if the forced frequency does not correspond to the free frequency then waves advancing will interfere with waves reflecting. This is because the velocity in both directions is identical and equal to

$$\sqrt{\frac{T}{M}}$$

per Formula 1; and because the wave length is fixed from Formula 2

$$L = \frac{V}{N}$$

where wave velocity and frequency are fixed. When a wave length therefore is imposed by forcing an "unnatural" frequency, the resultant forced wave length would not be an even multiple of the free span and the reflecting waves would try to have a node where the approaching waves try to have a loop. The string would adopt a resultant shape from the two actions and the result is termed wave interference.

Various forced frequencies may be impressed at a paper-machine mesh unintentionally by such as screen and fan pump impulses in the jet, or slight eccentricity in carry rolls, and intentionally by special vibrators such as ultra-sonic devices. Thus it can be desirable in some papermaking conditions to impress a non-resonant frequency on the mesh thereby to interfere with waves from jet impulses and mechanical imbalances.

Control of wave length

Except where there is a forced vibration, the wave length for free vibrations will be a multiple of the free span of mesh between breast roll and drum. This horizontal segment of mesh can be made to vibrate with any desired number of nodes and loops, without table rolls, merely by damping the mesh at a point to cause any desired harmonics.

For example, damping the mesh at a point $\frac{1}{4}$ the distance from one end will cause the mesh to vibrate in four loops instead of a single loop with a node at the point of damping. Further, a string may vibrate with

more than one mode of vibration at a time. For example, if a string is struck $\frac{1}{4}$ the distance from one end, it may vibrate not only as two loops but simultaneously as a single loop. From $V=NL$, these short loops will have twice the frequency of the long loops and if such frequencies are in the audible range they will sound an octave apart. The single loop provides the fundamental frequency and the double loops a harmonic frequency. Thus, "tuning-up" a paper machine takes on a literal meaning because an experienced papermaker is given a new and unexpected value to his sense of hearing through the present invention.

From Young's law, when a string is struck at any point only those modes of vibration are set up which do not have nodes at that point. Conversely, when a string is touched at any point all vibrations are damped that do not have nodes at that point. It is clear from Young's laws, that in order to stop all vibrations of a string, it should be damped at the same point where it is struck. This is done for example in the piano.

Therefore one way to change the wave length in a papermaking mesh is to touch the mesh with a doctor blade, or else some object such as a roll, where a node is wanted.

Another way to change wave length is to change the free span of mesh by extending a forming board under the mesh. A forming board is especially effective in damping vibration, if we heed Young's law by placing the forming board to include the area where the jet strikes the mesh. If a wave is not started there is no wave to transmit.

A further way to change wave length is to change the distance between breast roll and drum. This is not easily done, and thus is not practical because it requires either sliding the breast roll and headbox with its piping, or else sliding the drive and drum which in some alternative constructions includes suction apparatus.

Of some further ways to change wave lengths, one is to move the point where the jet strikes the mesh by changing the trajectory, and another is to adjust an apron cloth in its mass and distance out from the bottom slice lip.

One would choose any of these and other ways to change wave lengths according to whichever is suited to prevailing conditions.

Control of velocity of wave

The velocity of a wave in the mesh may be determined from Formula 1, namely

$$V = \sqrt{\frac{T}{M}}$$

Thus, for a fixed mass, if we quadruple the tension, we double the wave velocity. If we increase or decrease tension and mass simultaneously in equal proportions, the expression

$$\sqrt{\frac{T}{M}}$$

remains constant and there will be no change in wave velocity.

From Formula 2, namely $V=NL$, for a fixed frequency, if we double the wave length we double the wave velocity. Also, for a fixed wave length if we double the frequency we double the wave velocity. If we increase the frequency in the same proportion as we decrease the wave length, the expression NL remains constant and there will be no change in wave velocity. If we increase frequency and wave length together then we increase wave velocity very quickly.

We can thus change wave velocity a measured amount by imparting a measured change to any or all of the factors, frequency and wave length by means already

explained, and tension and mass by means to be explained in detail later.

Also it has been shown that when the velocity of the wave reaches the Critical Speed, the bends in the mesh become "frozen" in place. It is of course possible to drive the mesh and fibres faster or slower than this Critical Speed if desired and to "rush" or "drag" the jet relative to the mesh according to usual papermaking practice. In such an event the mass M for Formulas 2 and 3 has its velocity made up of two parts, one part for the mesh, and one part for the fibres in liquid suspension.

Control of mesh tension

Mesh tension is regulated directly at a carrying roll, by conventional belt take-up means, with provision for measuring the load. The effect of tension on vibration is seen in Formulas 1 and 3 and has already been explained.

Control of mass per unit length

For the small amplitude of vibration in this method and apparatus, the masses of mesh and overlying fibres in liquid suspension have been considered as one mass. This is not strictly correct, and it has been explained above that the liquid does not carry tension and thus does not supply centripetal force (as a mesh does) except for the liquid surface tension. Thus, the treatment of the combined mesh and liquid in this invention according to the physical laws of vibration in a string is an approximation, but a valuable one. Therefore in papermaking the various magnitudes would be set according to these laws and then adjusted to yield optimum results, according to the qualities wanted in a given grade of paper.

Mass may be changed in any of several ways including combinations of these ways. Firstly, the jet may be speeded while other conditions remain constant, whereby the mass per unit length of mesh will increase directly as the speed increases. That is, if the jet speed for example is doubled, the mass per unit length is doubled.

Secondly, the jet may be thickened by raising the top lip of the slice. For example doubling the jet thickness while other conditions remain constant, would double the mass per unit length of mesh.

As both methods would increase the quantity of fibres per unit length of mesh, these methods should be accompanied by usual means to lessen the concentration of fibres in the headbox in order to maintain a constant basis weight. That is, we should provide the extra mass by adding water only, not fibres.

Thirdly, an adjustable apron cloth has already been suggested above as one means of changing mass, for at least part of the mesh span.

Fourthly, the mesh may be speeded or retarded to change the distribution of mass per unit length. Of several other ways to change mass per unit length of mesh, one for example is to introduce additives to the liquid such as clay to make it heavier or air bubbles for example to make it lighter; another is to use a liquid of different specific gravity such as thick black liquid from kraft pulping.

Example

Having explained the theory and application of the instant invention, a typical calculation may be made as follows.

A Fourdrinier travelling at say 1800 ft./min. (30 ft./sec.) with table rolls at 1.5 ft. centre-to-centre spacing produces table-roll impulses of

$$\frac{30}{1.5}$$

equalling 20 vibrations/sec. It is well known that the combination of mesh speed, mesh tension and deflecting force at Fourdrinier table rolls is enough to bounce liquid off the free surface and across as many as 5 table rolls before landing. A table roll cannot drain liquid which is

as droplets in mid air. Thus, table-roll vibrations hinder drainage and disrupt formation thereby weakening the sheet.

In contrast, to the Fourdrinier the present invention has no strong drag to cause an abrasive creep from differential tension at the drive roll and has no flat boxes to abrade the mesh. Firstly, this elimination of drag and creep frees a part cross-sectional area of each tensile thread to be loaded for tension, instead of being reserved for abrasion. Secondly, this elimination of drag and creep frees the mesh from having a maximum tension between a last flat box and couch, and permits letting the maximum tension pervade the entire mesh circuit, especially pervading the former zone of table rolls previously a zone of weak tension.

One new result from these two tensile effects is that an extra range of tension is introduced, at the delivery zone of the jet, which is not possible with a Fourdrinier. Thereby a new wide range of control is achieved.

Another new result is that the number and rate of vibrations may be controlled without reference to table-roll quantity. For instance, we can provide either the same rate or else the same number of vibrations as in the above Fourdrinier example merely by controlling the number of vibration loops.

Firstly, for the same rate of 20 vibrations/sec., at 1800 ft./min. we would merely set up the previous wave length of 1.5 ft. Thus if we choose say a 6 ft. span for an example with the present invention, then we would need

$$\frac{6}{1.5}$$

equalling four waves or eight loops. Such loops would be achieved by damping the mesh, by such as a doctor blade or roll, at

$$\frac{1.5}{2} \text{ ft.} = .75 \text{ ft.}$$

from the breast roll. If one wanted maximum vibration the jet should impinge at the centre of this .75 ft. loop. The height for a horizontal jet at 1800 ft./min. to impinge at half .75 ft. by free fall calculates to about .001" above the level of the mesh. Such a flat trajectory needs to be adjusted for any air current induced by mesh movement and for the phenomenon of any ascended loop intercepting the jet at a point nearer the slice than a descended loop. The same vibration could be imparted by impinging the jet at the centre of the second loop, in this example, namely .75 ft. beyond the point of damping.

As already explained, one of several ways of damping such vibration or flutter is to extend a forming board under the zone of impingement. In the instant invention, by duplicating the rate of vibration in the Fourdrinier example, the shorter length of the instant invention would result in fewer total vibrations than on the Fourdrinier.

Secondly, for the same total number of vibrations as in the Fourdrinier example, we would need 20 vibrations in the 6 ft. span between breast roll and drum. Thus we would need to increase from the above 4 waves to 20 waves. Such a fivefold increase would require dividing each of the 4 waves into 5 sub-waves, whereby the new wave length would be $\frac{6}{20}$ equalling .3 ft., and each loop length would be

$$\frac{6 \text{ ft.}}{40 \text{ ft.}}$$

equalling .15 ft.

Such a close position to the breast roll for a first node would make it more practical to damp at a node some multiple of .15 ft. from the breast roll. In this example, we would want to avoid damping at any loop quantity which is a factor of 40 or any even number, namely at every 2nd or 5th node, because such points would be in common with longer loops. For example if we damped

after the 2nd loop of 40, the wire could revert to 20 loops, being 10 waves instead of the desired 20 waves. Thus we could damp in this example after the 1st, 3rd, 7th, 9th, 11th, 13th, 17th and 19th loops and maintain the desired 20 waves.

The present invention however is not restricted to reproducing either the same total rate or else the same number of vibrations as on a Fourdrinier, and instead may be adjusted to any frequency desired, including a virtual elimination of vibration by means above described. The present invention thus introduces a new wide range of vibration to papermaking with means to control that vibration all achieved with simple and rugged equipment.

In the above example, if one wanted to set the wave velocity to equal the jet velocity, then one would proceed to set the tension for this Critical Velocity something as follows. Assume as above that liquid and mesh act together as a single mass, because the amplitude is so small, and then calculate wave velocity from the vibration formulas.

Firstly calculate the mass per unit length of mesh. For a 1 ft. width of mesh, and a jet thickness of the order of say 1 inch, the mass including mesh is approximately 5.2 lb./ft. of the travel direction or span.

Secondly at the Critical Speed, velocity of the combined mesh and jet mass equals velocity of wave, which in the above example requires causing the velocity of wave to be 1800 ft./min. being 30 ft./sec.

$$V = \sqrt{\frac{G \times T}{M}} \quad 30 \text{ ft./sec.} = \sqrt{\frac{T \text{ lb.} \times 32.2 \text{ ft./sec./sec.}}{5.2 \text{ lb./ft.}}}$$

$V = \text{ft./sec.}$

$G = 32.2 \text{ ft./sec./sec.}$

$M = \text{lb./ft.}$

$T = \text{lb.}$

$G = \text{gravitational constant}$

$T = \text{total tension of the wire in lbs.}$

$M = \text{mass of wire and slurry combined}$

For 1 ft. width $T = 145 \text{ lb.}$

For 1 inch width $T = 12.1 \text{ lb.}$

This is well within the working tension of papermaking mesh.

If we permit the span of the above example to vibrate freely as a single loop, then the wave length is 2 loops or 12 ft. From Formula 2, and using the Critical Speed, where velocity of mesh and jet mass equals velocity of wave. The frequency is:

$$N = \frac{V}{L} = \frac{30 \text{ ft./sec.}}{12 \text{ ft./cycle}} = 2.5 \text{ cycles/sec.}$$

$V = \text{velocity of a wave}$

$L = \text{length of a wave or cycle.}$

These calculations thus indicate that using the same jet speed as the Fourdrinier, namely 1800 ft./min., the present invention provides a way and means whereby it also may travel at the same 1800 ft./min., and at the same time make vibrations advance also at 1800 ft./min. merely by tightening the mesh to 12.1 lb./inch including adjustments for the theoretical considerations of mesh and liquid acting as a single mass. This is the Critical Speed where the mesh waves will follow a curved path stationary relative to the ground, and the waves thereby appear "frozen" in position. The time for traversing the 6 ft. span of the example, at 1800 ft./min. is only $\frac{1}{6}$ sec. and therefore high-speed techniques would be needed to see the phenomenon. Some correction coefficients are needed also because the tangent point of the horizontal mesh-segment

to drum is ill-defined, when the stock layer has the mesh deflected from the drum during normal operation. In practice a papermaker can adjust to values which are found to produce the best results for given grades of paper.

It is possible for example to quadruple the above 12.1 lb./inch to 48.4 lb./inch and double the wave velocity. This would double the number of vibrations from 2.5/sec. to 5/sec. while the mesh speed remains unchanged. Also, one could damp the mesh at a quarter point and quadruple the number of vibrations.

It is preferable, but not obligatory, in the present invention to eliminate all table rolls. Alternatively, table rolls also may be spaced to cause wave interference. Those skilled in the art will appreciate that the minimum free span between breast roll and drum will always be sufficient to permit flexure of the mesh for controlled entry of ribbon of stock. The maximum free span will be limited by the acceptable amount of mesh sag depending on mesh tension and mass and velocity of stock. All the above on vibration is directed toward controlling fibre flocculation and alignment and thereby to controlling paper strength and quality.

Drainage capacity

Paper quantity on the other hand may be increased by a method and means, explained below, which is in combination with and acts as an integral part of the vibration-control-part.

The present invention increases drainage capacity over known methods, and especially over the cylinder machine and Fourdrinier, by intensifying the drainage action necessary in pulp and paper sheet formation. This increase is achieved by having a mesh part wrapped around a substantial arc of a drum, whereby mesh tension causes a pressure radially toward the drum periphery, and a layer of fibres in liquid suspension is squeezed between mesh and drum. A fibrous sheet thereby is felted together and formed while liquid is squeezed through the mesh part.

Besides papermaking, this method and means for sheet forming is useful also for draining pulp to make laps or board, and treating fibrous or finely-divided materials which are suspended in chemical liquors.

Examples would be the separation of bleach and cooking liquors from pulp, the removal of precipitates such as lime in kraft pulping liquors, the separation of liquids from food mashes, and the separation of solids from oily and tar-like mixtures.

This structural combination introduces the new results of solids in liquid suspension being agitated controllably, for controlled sheet strength, and being drained intensively for quick formation and big capacity.

I claim:

1. Apparatus for forming a sheet from fibres in liquid suspension comprising in combination: a first substantially-horizontal segment of an endless-mesh means for traveling with and supporting a ribbon-like layer of fibres in liquid suspension; carrying rolls for said mesh means including a drum mounted for rotation about a horizontal axis with the outer surface of said drum tangent to said horizontal segment of mesh; a second segment of said endless mesh means formed in a loop wrapped around a substantial arc of said drum for guiding said layer of fibres around said drum outer surface against centrifugal force; tension-control means acting on at least one of said carrying rolls and adjustably maintaining a substantially-constant tension throughout said mesh for providing a constant mesh-pressure acting on said fibres resisting centrifugal force and providing a magnitude of tension T in said horizontal segment of mesh; stock delivery means to set a magnitude M of fibre mass distributed on said horizontal segment of mesh; said horizontal segment of mesh having a magnitude N of frequency; and span adjustment means to set a magnitude L of wave length in said first segment of mesh; whereby any three of said T, M, N, and L are chosen magnitudes and the remaining

fourth magnitude is derived from the general wave formula

$$\sqrt{\frac{TG}{M}} = NL$$

in which each side of said formula represents wave velocity, and thereby is a means to predetermine the amount of vibration and thus fibre interlocking and quality of a self-supporting sheet.

2. An apparatus as claimed in claim 1 wherein said tension-control means includes a tension regulator operatively connected to said one roll and includes variable pressure loading means.

3. An apparatus as claimed in claim 1 wherein said drum is provided with an imperforate outer surface.

4. An apparatus as claimed in claim 1 wherein said drum is provided with a perforated outer surface, vacuum means connected to said drum, said endless mesh means consisting of a first endless screen surrounding said drum in said substantial arc and providing said substantially horizontal segment of said endless mesh, and a second endless screen having a portion disposed between said drum outer surface and said first screen, and a further portion extending in parallel spaced relationship to said first screen horizontal portion whereby, said ribbon-like layer of fibres is delivered between said first and second screens.

5. An apparatus as claimed in claim 1 wherein said drum is provided with a perforated outer surface, vacuum means connected to said drum, said endless mesh means consisting of a first endless screen surrounding said drum in said substantial arc and providing said substantially horizontal portion of said endless mesh, and a second endless screen having a portion overlapping said drum surrounding portion of said first screen whereby, said ribbon-like layer of fibres is delivered to said first screen horizontal portion and carried by said screen portion between said overlapped first and second screen portions.

6. An apparatus as claimed in claim 1 wherein a head-box including adjustable slice means is positioned to deliver said ribbon like layer of fibres in liquid suspension to said mesh means horizontal segment, said headbox and slice means being disposed adjacent said horizontal segment of said mesh at a point spaced from said loop segment.

7. An apparatus as claimed in claim 1 wherein deckle means are disposed at each side margin of the upper surface of said mesh horizontal segment and further deckle means are disposed at each side margin of and bearing against the exterior surface of said mesh loop segment surrounding said drum substantial arc.

8. An apparatus as claimed in claim 1 including vibrator means engaging said mesh horizontal segment to impart vibrational motion to said mesh segment for augmenting natural wave frequencies imparted thereto by the operational movements of said mesh during its travel about said carrying rolls and drum.

9. The method of forming a sheet from fibres in liquid suspension comprising the steps of: delivering a substantially-horizontal and ribbon-like jet of fibres in liquid suspension to a substantially-horizontal free-span portion of an endless mesh means and supporting the fibres thereon; driving said horizontal-mesh portion in the same direction as said jet; imposing a wave velocity V in said free-span to control flocculation and interlocking of fibres by adjusting mesh tension T to a chosen value by tension-control means and mass M to a chosen value by mass control means, wherein said T and M values determine the value of V according to the classic wave formula

$$V = \sqrt{\frac{GT}{M}}$$

in which V is the wave velocity in ft./sec., G is the

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gravitational constant 32.2, T is the total mesh tension in pounds, and M is the mass of the mesh and fibres in liquid suspension per linear foot, and draining said fibres to form a continuous fibre layer; and removing said layer from said mesh means as a self-supporting sheet.

10. The method of claim 9 including the step of imposing a supplemental vibration to said free-span portion to augment natural wave frequencies imparted thereto when said free-span portion is driven.

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