

A FUNDAMENTAL OPPORTUNITY TO IMPROVE PAPER FORMING

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UNIFORMITY OF PHYSICAL PROPERTIES OF PAPER manufactured for printing, packaging, and other applications continues to be one of the most serious quality issues in today's mills.

Quality issues such as the small-scale variations in basis weight, density, and fiber orientation will become considerably more important in the mill of the future. The reason is threefold: continuously increasing demand for higher quality by the consumer; new technologies in consolidation, finishing and converting; and the requirement to lower rejects and boost productivity.

The entire sheet characteristics and behavior are based on the physical properties of the fiber, the fiber network structure including density and fiber orientation, and the basis weight of the sheet. Uniformity of these characteristics is most important, since many other physical properties are influenced to various degrees in the forming process based on these fundamental characteristics.

The fiber network structure and the basis weight take form in the headbox and on the forming table. This is the reason that many experienced papermakers believe that the headbox and the forming table are the most critical process in paper forming.

The large scale "average" basis weight and moisture profile variations with a span greater than 6 in. in CD can be controlled effectively with today's technologies. However, small-scale physical property variations that span from 0.5 to 4 in. are often not detected on-line and, consequently, are not controlled. These small-scale nonuniformities in physical properties cause many problems in converting and printing. Paper rejects because of quality issues are of common concern in today's mills.

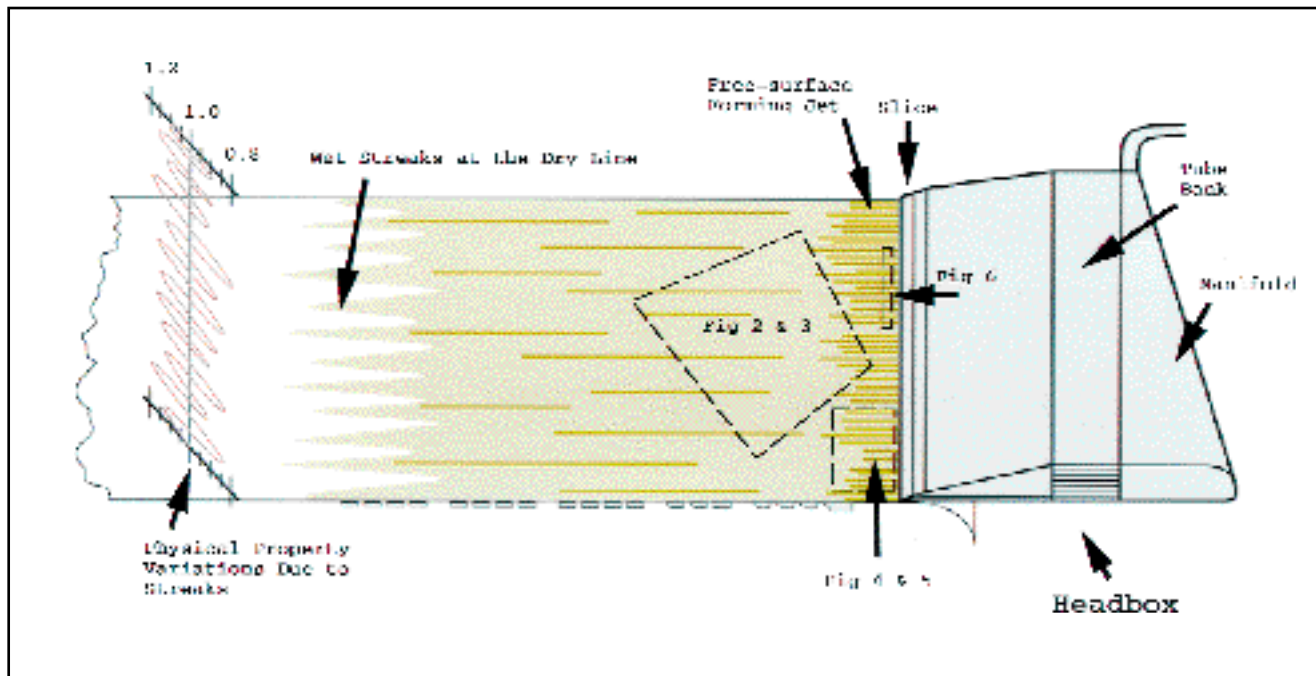
SMALL-SCALE VARIATIONS

High-resolution measurements with more than 30 points/in. (1) show that in most of today's commercially manufactured paper and board, small-scale basis-weight variations range from 5% to 20% with peak to peak CD span of 0.5–4 in. High-resolution basis weight measurements of any commercially produced sheet with less than 5% variation have not been seen. Relatively large variations in other physical properties such as fiber orientation and sheet density are present over the same length scale. The magnitude of the small-scale variations is much larger than the measurements provided by the low resolution on-line sensors.

STREAKS ARE NOT CAUSED BY RANDOM TURBULENT FLUCTUATIONS. THEY ARE DETERMINISTIC AND ORIGINATE IN THE HEADBOX DUE TO SMALL-SCALE SECONDARY FLOWS. OFTEN OVERLOOKED IN TODAY'S MILLS, THESE NONUNIFORMITIES WILL BECOME MORE IMPORTANT IN THE MILL OF THE FUTURE.

Variations in basis weight and moisture streaks could have many causes. They are categorized into three classes: (a) nonuniformity in fiber concentration or consistency, (b) nonuniformity in mass distribution on the forming wire or forming table, and (c) nonuniform drainage in the forming section. Of these, the second and third mechanisms relate to the dynamics of the formation process. The hydrodynamics of the headbox, the characteristics of the free surface forming jet, jet impingement, and the evolution of the layer along the forming section are the key parameters discussed here.

The magnitudes of the small-scale fluctuations in basis weight are often considerably larger than the magnitude of the basis weight variations recorded by the on-line sensors. Since the performance and strength of the product usually depend on the magnitude of the variation in physical properties, the small-scale fluctuations could be more important than the overall averaged nonuniformities. The small-scale fluctuations in elastic stiffness can be caused either by small-scale variations in fiber orientation or by the nonuniform drying rate due to moisture streaks in the sheet. These nonuniformities can



1. Schematic presentation of the streaks on the forming table. Location of the images presented in Figs. 2–6 are outlined.

be caused by streaks in the forming section. An analysis of the streaks on the forming table determines whether they are the result of random turbulent fluctuations or deterministic secondary flows.

EVOLUTION OF STREAKS

Turbulent flow, by definition, is a combination of high frequency undeterministic random flow fluctuations superimposed on a deterministic mean flow. The time-frozen snapshot of the velocity profile in a turbulent flow shows many fluctuations with an average trend. If a large number of the instantaneous turbulent profiles are added and averaged together, then a smooth profile, referred to as the mean turbulent profile, emerges. In contrast to the random turbulent fluctuations, the mean turbulent profile is a deterministic or predictable quantity.

Detailed high-speed digital imaging of the forming table is one of the methods used at IPST to study the physics of paper forming. The high-speed images can be taken up to 4000 frames/s with an exposure time as short as 1 microsecond. The small exposure time of a single frame captures the forming layer in a time-frozen form showing the details of the small-scale fluctuations due to turbulent flow. This approach is demonstrated below in the analysis of various regions of the forming section as outlined in Fig. 1. A single frame of the flow over a large section of the forming table is shown in Fig. 2. The machine speed is at 3000 ft/min making base sheet for a coated grade. In this view, the slice and the impingement line are covered by the headbox, as indicated in the figure. This image shows many small scale fluctuations on the forming table. A time-frozen image, as

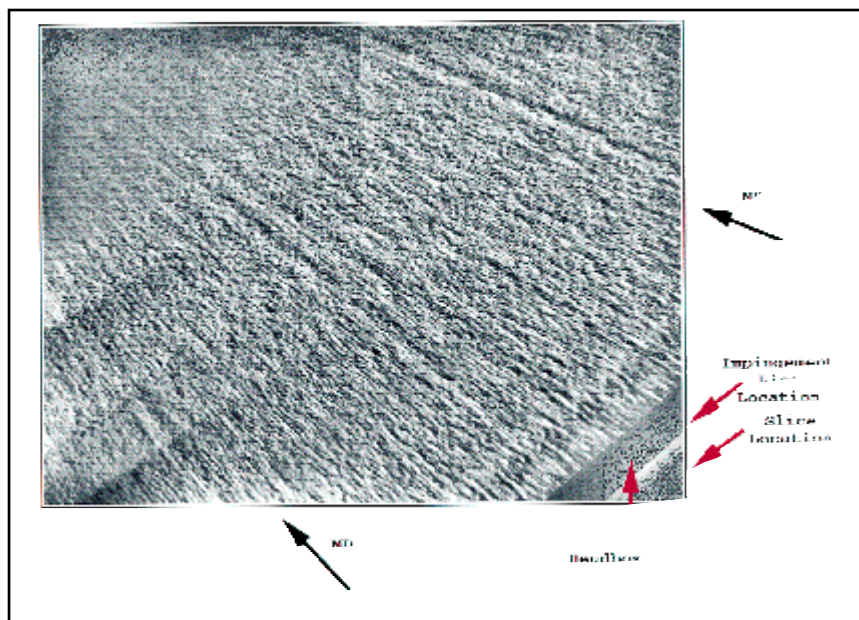
indicated below, is a superposition of randomly occurring flow fluctuations on the mean flow. However, from this image, it is not clear whether there are consistent regularly patterned streaks on the forming table. To examine this, one has to remove the random fluctuations and look at the mean flow.

By averaging these images over several hundred frames, we can remove the small and randomly occurring feature from the image and examine the mean flow. Since the images are in digital form, we have developed methods to greatly enhance the image and to take the average of a specified number of images*. For this machine speed, an exposure time of 50 microseconds is found to be sufficient. The average flow over 500 frames, each with an exposure time of 50 microseconds taken at a rate of 1000 frames/s covering 0.5 s in real time, is shown in Fig. 3. This image clearly shows that there is a consistent streak pattern in the mean flow over the forming table.

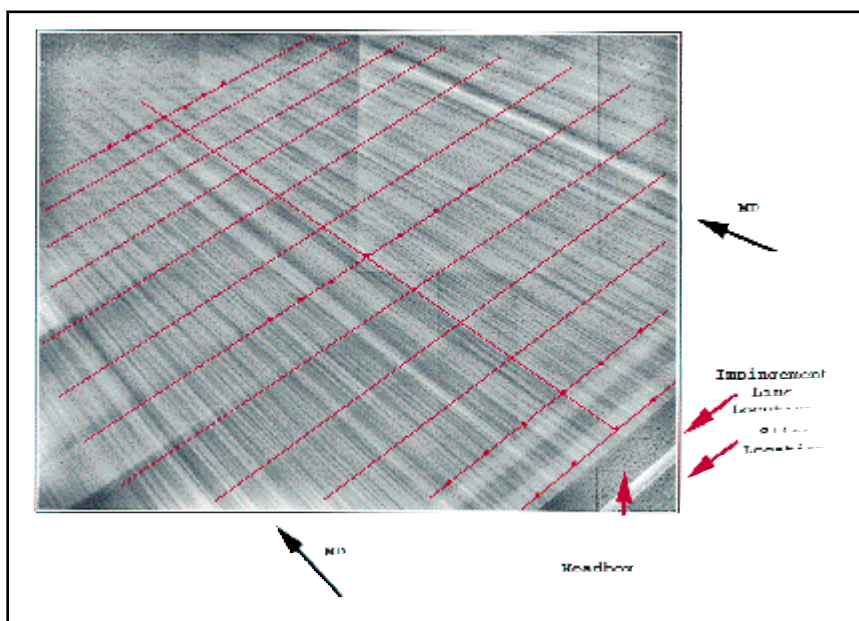
ORIGIN OF STREAKS

Taking a closer look at the forming jet delivered at the slice, the enhanced time-frozen image of the forming jet and the impingement line is shown in Fig. 4. This image clearly shows streaks in the forming jet that amplify upon impingement on the forming wire and result in some degree of stock jump. Some believe that the streaks in the forming jet are caused by turbulent fluctuations

*The averaging method used here is not to be confused with the long time exposure methods. With long time exposure, a moving point will leave a continuous streak on the image. With our method, a moving point leaves N number of points on the image each with a gray level intensity of $1/N$ of the original intensity, where N is the number of frames used in the process.



2. Time-frozen image of the flow over the forming table. The slice and the impingement line are not visible in the image. Their general location along with the MD is pointed out in the figure. (Machine speed is 3000 ft/min. The exposure time of the image is 50 microseconds.)



3. Average of 500 images of the forming table shown in Fig. 1 covering a period of 0.5 s. The red lines and dots show a 12-in. length scale in MD and CD, respectively.

inside the headbox and, therefore, occur randomly in the system. In Fig. 5, it is clear from the averaged result that the streaks appear consistently, not randomly, in the forming jet. Turbulent fluctuations, however, appear randomly. Therefore, the streaks in the forming jet are not the result of turbulent fluctuations.

The streaks in the forming jet, such as those in Fig. 5, are caused by the secondary flows induced by the jets from the tubes. These secondary flows are spatially periodic, in nature. That is, there is a given CD span over which

the structure of the flow pattern repeats. The CD dimension of this periodic pattern is the width or the wavelength of the secondary flow. The wavelength of the tube jet-induced secondary flow is not necessarily equal to the CD spacing of the tubes in the tube bank. The secondary flows often appear in the form of recirculation vortices, which are superimposed on the main stream flow. Secondary flows, not to be confused with turbulent fluctuations, are a deterministic part of the flow generated by various mechanisms and can be computed using the mean form of the momentum equation and appropriate turbulent models (2). Examples of small-scale secondary flows in the headbox due to tube jet interactions will be submitted for future publications.

These secondary vortices, once relieved from the confined boundary of the headbox slice, will deform the free surface of the liquid into the streaks as seen in Fig. 4. The upward and downward streams in the secondary flow form the crest and the trough of the streaks, respectively. The structure of the streaks that form at the slice depends directly on these secondary flows in combination with the nature of the headbox converging zone and the slice geometry. In some cases, there are two streaks generated per each column of tubes. Every pair of streaks corresponds to a column of tubes. Other types are when streaks form from jets delivered by staggered tubes where a weak secondary streak exists next to a stronger primary streak. Computational analysis of the interaction between the tube jets inside the headbox reveals the precise form of these secondary flows. More details will be presented in future publications.

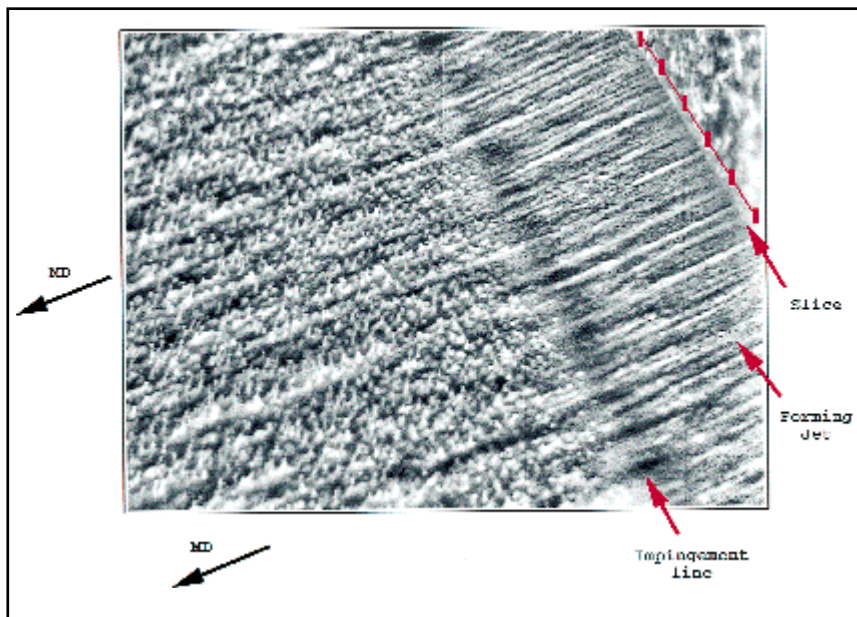
DYNAMICS OF THE STREAKS

Streaks on the forming table are caused by nonuniform or secondary

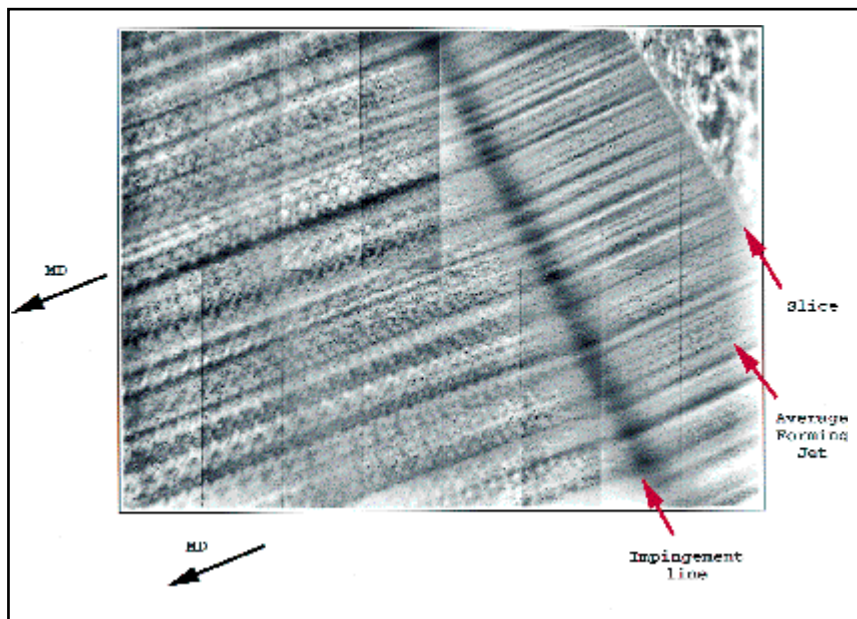
flows in the headbox, the jet interaction with the wire, and the fluid dynamics of the free surface flow on the forming table. With most forming sections, one can immediately see the narrow streaks that form near the slice. These streaks are 0.5 to 4 in. wide and correspond to the small scale secondary flows emanating from the tube jets inside hydraulic headboxes or the wake of holes in the slice rectifier roll.

The physics and dynamics of the forming jet delivered by the headbox can be analyzed with time-line images, as shown in Fig. 6. In this headbox, the spacing between the tubes in each row is about 1 in. and the tubes have a staggered pattern, and considering the average streak width in Fig. 5 and 6, one can state with some confidence that the streaks are due to the secondary flows from the jets delivered from individual tubes in the tube bank. Looking at Fig. 6, careful analysis of these time line images shows that the jets from adjacent tubes from two rows (i.e., ~0.5 in. apart in CD) interact and compete with each other to leave a streak in the forming jet. Through this interaction, the streaks are deflected sideways. The interaction and subsequent deflection of the tube jets in the headbox result in sideways flapping-like motion of the streaks in the forming jet. The sideways motion of the streaks in the forming jet have significant impact on the small-scale fiber orientation and formation in the sheet. In fact, the small-scale variations in fiber orientation are caused by the local dynamics of the streaks in the forming jet.

Although only the images of the top of the forming section are presented here, the streaks should be viewed in terms of secondary flows throughout the forming jet. Similar streaks exist at the underside of the



4. Time-frozen image of the forming jet, jet impingement region, and the stock activity after the impingement line. The red marks show a 1-in. length scale. (Machine speed is 3000 ft/min. The exposure time is 50 microseconds.)

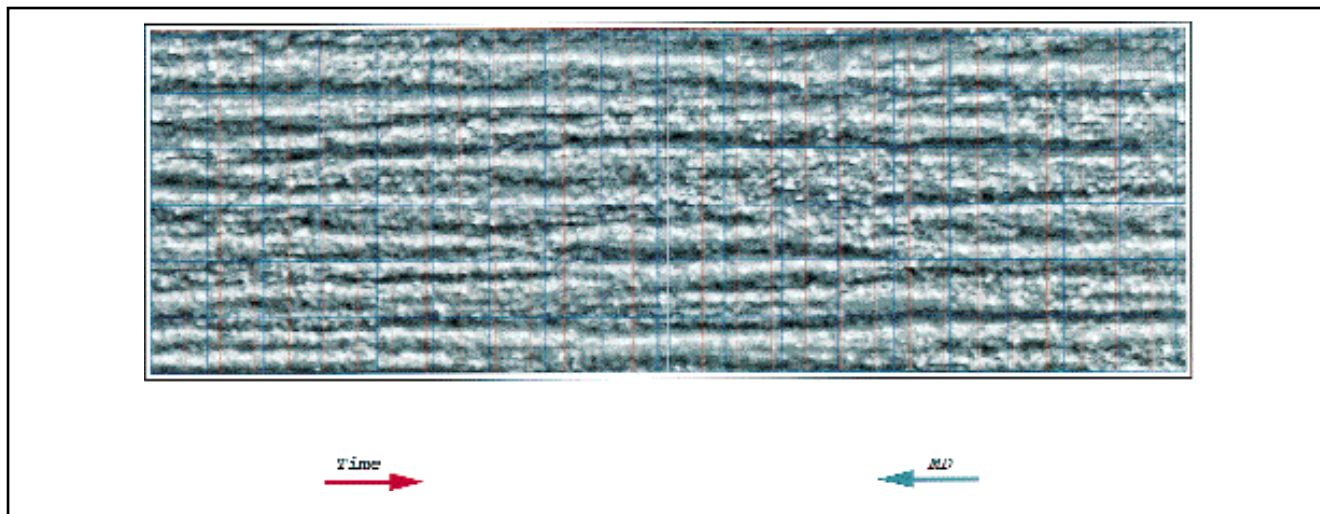


5. Average of 500 images of the forming region shown in Fig. 4 covering a period of 0.5 s.

forming jet. Interaction of these streaks with the wire determine the structure of the sheet.

IMPACT OF STREAK DYNAMICS

The variation in angle of the forming jet streaks with the machine direction from the time-line images is approximated in Fig. 6. If the distance from the tube outlet to the slice is 29 in. and the distance from the slice to the impingement line is 6 in., then for every 0.1 in. that a streak moves in the



6. Time-line projection of the forming jet at 1 in. from the slice showing the dynamics of the streaks delivered from the headbox. The blue grid lines provide a 1-in.² length scale. The 30 sections outlined by the red lines are the time-sequence images of a 0.6-in. section of the forming jet stacked on top of each other over a 30-millisecond period imaged at 1000 frames/s with an exposure time of 50 microseconds.

cross-machine direction of Fig. 6, the angle of the streak changes roughly by $\tan^{-1}(0.1/30) = 0.2$ degree. Considering that fiber orientation is governed by the direction (or angle) of the shear field in the forming layer, this variation in the local forming jet angle would result in significant fiber misalignment and fiber orientation nonuniformity over a small CD length scale. The magnitude of the variation would depend on the forming jet angle and the rush/drag ratio. If one takes the first layer of fibers from the wire side and measures the small-scale in-plane fiber orientation variation, we predict that the CD length scale of the variations would be in the order of the streaks length scale in the forming jet.

Jet/wire interaction and the evolution of the streaks along the forming section have significant impact on the small scale basis-weight and moisture profile. The mechanism and interaction between the layer on the forming section and the formation characteristics on the wire is currently under study.

To eliminate the nonuniformities in physical properties caused by the streaks in the forming section, the small-scale secondary flows induced by the tube jets inside the headbox must be eliminated.

CONCLUSIONS

The origin of the layer nonuniformity in the forming section is the nonuniform free surface jet delivered by the headbox onto the forming wire or into the gap former. Small-scale disturbances, secondary flows, and turbulence are generated by the headbox. The characteristics of the jet impingement on the wire defines the degree of amplification of these disturbances. The role of the forming wire is to determine the relation between the disturbances and secondary flows in the headbox with the

fiber mat formation characteristics. Once the fiber mat has formed, that is after the dry line, the last two of the three fundamental physical properties are set in the sheet.

The headbox geometry and dimension, along with the flow rate and fluid properties, set the level of turbulence in the forming jet. The dimension, separation distance, and the pattern or arrangement of the tubes in the tube bank along with the converging angle of the headbox and the slice lip determine the magnitude, dimension, and the dynamics of the small-scale secondary flows and, consequently, the characteristics of the streaks in the free surface forming jet delivered at the slice.

The jet impingement on the forming board results in the amplification of the disturbances where the degree of amplification is proportional to the impingement angle. That is, the larger the impingement angle, the larger the amplification of the disturbances. This is due to an acceleration-induced instability, which is well understood.

As the streaks form in the forming jet, amplify upon impingement, and evolve along the forming wire, there is a characteristic growth and decay rate associated with the streaks. The growth and decay rates determine the rate of growth and decay of a streak on the forming wire. Analysis of the streak formation and decay (3) shows that these rate factors depend on the turbulence level of the flow, the average thickness of the layer, and the width (or wavelength) of the streaks. In general, the very narrow streaks grow and decay very rapidly. The growth rate of the wide streaks is relatively small. As the disturbances and streaks evolve through the forming section, the narrowest streaks form and decay not too far from the forming board. Gradually wider streaks form down

the forming section. Depending on the wire speed and the growth and decay rates, streaks with a critical width dominate the surface characteristic of the forming layer at the dry line.

The interaction and dynamics of the tube jets inside the headbox result in small-scale CD oscillation or flapping of the streaks in the forming jet. This small-scale CD motion results in small-scale variations in fiber orientation and fiber network in the sheet. The most effective mechanism to eliminate this fundamental defect in paper forming is to eliminate the small-scale secondary flows induced by the tube jets by generation of controlled axial vorticity and swirl in the headbox (4, 5). **TJ**

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