STATUS REPORTS

To The

PAPER PHYSICS

PROJECT ADVISORY COMMITTEE

April 29, 1993
INSTITUTE OF PAPER SCIENCE AND TECHNOLOGY
PURPOSE AND MISSION STATEMENT

The Institute of Paper Science and Technology is a unique organization whose charitable, educational, and scientific purpose evolves from the singular relationship between the Institute and the pulp and paper industry which has existed since 1929. The purpose of the Institute is fulfilled through three missions, which are:

- to provide high quality students with a multidisciplinary graduate educational experience which is of the highest standard of excellence recognized by the national academic community and which enables them to perform to their maximum potential in a society with a technological base; and
- to sustain an international position of leadership in dynamic scientific research which is participated in by both students and faculty and which is focused on areas of significance to the pulp and paper industry; and
- to contribute to the economic and technical well-being of the nation through innovative educational, informational, and technical services.

ACCREDITATION

The Institute of Paper Science and Technology is accredited by the Commission on Colleges of the Southern Association of Colleges and Schools to award the Master of Science and Doctor of Philosophy degrees.

NOTICE AND DISCLAIMER

The Institute of Paper Science and Technology (IPST) has provided a high standard of professional service and has put forth its best efforts within the time and funds available for this project. The information and conclusions are advisory and are intended only for internal use by any company who may receive this report. Each company must decide for itself the best approach to solving any problems it may have and how, or whether, this reported information should be considered in its approach.

IPST does not recommend particular products, procedures, materials, or service. These are included only in the interest of completeness within a laboratory context and budgetary constraint. Actual products, procedures, materials, and services used may differ and are peculiar to the operations of each company.

In no event shall IPST or its employees and agents have any obligation or liability for damages including, but not limited to, consequential damages arising out of or in connection with any company’s use of or inability to use the reported information. IPST provides no warranty or guaranty of results.

The Institute of Paper Science and Technology assures equal opportunity to all qualified persons without regard to race, color, religion, sex, national origin, age, handicap, marital status, or Vietnam era veterans status in the admission to, participation in, treatment of, or employment in the programs and activities which the Institute operates.
INSTITUTE OF PAPER SCIENCE AND TECHNOLOGY

Atlanta, Georgia

ANNUAL RESEARCH REVIEW

PAPER PHYSICS

APRIL 29, 1993
TO: MEMBERS OF THE PAPER PHYSICS PROJECT ADVISORY COMMITTEE

Attached for your review are Status Reports for projects to be reviewed and discussed at the Paper Physics PAC meeting scheduled for April 29, 1993, in Atlanta. A meeting agenda can be found inside the booklet.

Please note that the meeting is being held at the Institute of Paper Science and Technology.

We look forward to seeing you at this time.

Sincerely yours,

Maclin S. Hall
Associate Professor of Physics
Engineering and Paper Materials Division

MH/mp

Attachment
PAPER PHYSICS
PROJECT ADVISORY COMMITTEE

IPST Liaison: Mac Hall (404/853-9535)

Dr. Anil Sethy (Chairman)
Director Process Engineering
Packaging Corporation of America
5401 Old Orchard Road
Skokie, IL 60077-1073
708/470-5466 [6/93]*
708/470-3390 FAX

Dr. Leslie L. Martin (V. Chair)
Manager Papermaking R & D
Potlatch Corporation
Fiber R & D
P. O. Box 503
Cloquet, MN 55720-0503
218/879-2387 [6/94]
218/879-2375 FAX

Dr. Thomas E. Altman (Ted)
Research Scientist
Union Camp Corporation
P. O. Box 3301
Princeton, NJ 08543-3301
609/844-7428 [6/94]
609/896-1200 (ask for FAX)

Dr. Robert J. Niebauer
Project Manager, R & D
Crane & Company, Inc.
30 South Street
Dalton, MA 01226
413/684-2600 [6/95]
413/684-0726 FAX

Dr. George L. Batten, Jr.
Manager of Research & Development
Georgia-Pacific Corporation
2883 Miller Road
Decatur, GA 30035
404/593-6837 [6/94]
404/593-6801 FAX

Mr. Dirk E. Swinehart
Senior Research Specialist
Mead Central Research
Eighth & Hickory Streets
Chillicothe, OH 45601
614/772-3570 [6/95]
614/772-3595 FAX

Dr. Gary A. Baum
Director of Corporate R & D
James River Corporation
Neenah Technical Center
P. O. Box 899
Neenah, WI 54957
414/729-8403 [6/93]
414/729-8161 FAX

Dr. Thomas C. Kisla
Senior Engineer
Stone Container Corporation
1979 Lakeside Parkway
Atlanta, GA 30384
404/621-6714 [6/95]
404/621-6733 FAX

Dr. Keith A. Bennett
Senior Research Scientist
Weyerhaeuser Paper Company
WTC 2B42
Tacoma, WA 98477
206/924-6714 [6/93]
206/924-4207 FAX

*End of current term
PAPER PHYSICS
PROJECT ADVISORY COMMITTEE MEETING

April 29, 1993
Institute of Paper Science and Technology
Atlanta, Georgia

AGENDA

9:00 Welcome, Introduction
   IPST Antitrust Statement
   Sethy/Hall

   Mac Hall

10:15 Break

10:30 Fundamentals of Acoustic Radiation
   Pressure Effects on Wet Fibers
   Pierre Brodeur

11:30 - 1:00 Lunch

1:00 - 5:00 Committee Discussions
   Mac Hall
# TABLE OF CONTENTS

<table>
<thead>
<tr>
<th>Project</th>
<th>Title</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>3332</td>
<td>On-Line Measurement of Paper Properties</td>
<td>2</td>
</tr>
<tr>
<td>3767</td>
<td>Fundamentals of Acoustic Radiation Pressure Effects on Wet Fibers</td>
<td>34</td>
</tr>
</tbody>
</table>
ON-LINE MEASUREMENT OF PAPER PROPERTIES

STATUS REPORT

FOR

PROJECT 3332

April 29, 1993
Institute of Paper Science and Technology
Atlanta, Georgia
OBJECTIVE:

Develop sensors and instrumentation capable of measuring the velocity of ultrasound in the in-plane and thickness directions of paper while the paper web is moving at line speed. Shared support with Project 3613 (DOE Contract No. AC05-86CE40777).

GOAL:

The ultimate goal is to develop a commercially viable on-machine system, install a working system on a paper machine in a host paper mill, demonstrate the system’s capabilities and benefits to the paper manufacturing industry, and have a qualified vendor committed to supplying and supporting the system.

BENEFITS:

The measurement of the velocity of ultrasound provides a nondestructive means to characterize the mechanical properties of paper. Sensors capable of making such measurements in the thickness and in-plane directions of paper while the paper is moving at line speed on the paper machine would allow continuous monitoring of product quality as well as provide data for controlling the papermaking process.

For products requiring specific mechanical properties for end use, on-line measurement would permit the manufacturing process to be controlled to a stiffness target rather than a basis weight target. This would enable the manufacturer to reduce the amount of pulp and/or use a higher percentage of recycled fiber with confidence that the product remains within specifications.

Energy savings result from optimal use of energy intensive processes, such as refining; and from efficiency improvement in subsequent converting processes as a result of uniform product. Energy waste is avoided by minimizing substandard production.
TECHNICAL APPROACH:

Transducers mounted in fluid-filled wheels are used to make out-of-plane (ZD) ultrasound velocity measurements and caliper measurements on paper webs moving in the nip between two such wheels. Comparisons of the arrival times of echo and transmitted pulses with and without the paper web in the nip provide a measure of the transit time and caliper. Bimorph transducers mounted in an aluminum drum are used for in-plane machine direction (MD) and cross direction (CD) measurements.

The fluid-filled wheels and the drum with in-plane transducers are mounted on a reel-to-reel or endless belt web handling system in our laboratory. This web handling system includes a web guide and is capable of speeds up to 2500 fpm. A dancer arm provides adjustable tension in the loop mode, and tension is automatically controlled in the reel-to-reel mode. This system enables us to perform tests on rolls on 3 inch cores up to 14 inches wide and 34 inches in diameter or on 30-foot endless loops.

A test stand designed to operate with the unwind/rewind web handling system permits cross web positioning of the fluid-filled wheels in one inch increments. The wheel mounts are extended and retracted by air cylinders. Motors are provided to match wheel-to-web speed before closing the wheels onto the web. The spacing between the wheel axles (nip pressure) is adjustable. A commercial caliper gauge has been added to provide an alternate option for web thickness measurement.

The electronics used to make ZD and in-plane measurements on moving webs includes a four channel digitizing oscilloscope (LeCroy 7200) and a 486-type computer. A software package (WAVE), specially designed for manipulating and analyzing digitized waveform data, is used with the computer. Both ZD and in-plane moving web data have been collected on rolls of paper representative of a variety of commercial grades.

FLUID-FILLED WHEEL TRANSDUCERS FOR ZD MEASUREMENTS

Review of Past Project Activity - ZD Measurements

Two approaches for making measurements of the ultrasonic velocity in the thickness
direction (ZD) of moving paper webs have been developed. One uses IPST-made, elastomer-faced, PVDF wheel transducers, and the other uses modified, commercially available, fluid-filled wheels containing ultrasonic transducers. Our recent work has concentrated on using the fluid-filled wheels. The paper runs in the nip between two such wheels. They can be used to simultaneously measure both the ZD ultrasound transit time and the thickness from which the velocity is calculated.

A pair of identical flat-faced, narrow band immersion-type ultrasonic transducers with a center frequency in the range of 1 MHz to 2 MHz are used. This frequency range is a compromise between constraints imposed by increasing attenuation in paper at higher frequencies and the desire to use short pulses for accurate time measurements. One transducer serves as a transmitter, converting electrical energy to mechanical, while the other acts in reverse as a receiver. The transducers are each nested in a 7 inch diameter, fluid-filled wheel with a 3/8 inch thick rubber tire. The transducers are fixed in place facing each other, attached to axles around which each tire rotates. The axles are positioned so that the tires are in contact when there is no sample in place.

With this configuration, an electrical pulse sent to the transmitter causes an ultrasonic pulse to be launched from the transducer face. The pulse propagates through the fluid inside the transmitting tire, through the tire surface, across the nip where the tires meet, then through the surface of the receiving tire and the fluid inside it, finally striking the surface of the receiver, which converts the pulse back into electrical energy. In addition to this pulse, which propagates directly from transmitter to receiver, other later-arriving pulses are created at each boundary between different materials (i.e., transducer/fluid, fluid/rubber, rubber/paper) where partial transmission/reflection occurs. Each of these pulses has at some point bounced backward and forward once or more to arrive eventually at the receiver. Only a few of the resulting pulses (a pulse set) are of practical importance, arriving at the receiver with a time difference between pulses of interest of approximately 80 microseconds.

Standard immersion transducers are made with a one quarter wavelength plastic cover. We observed that the shape of the pulse reflected at the transducer is affected by this cover. To minimize the effect of this upon pulse time measurements, we purchased special transducers made with a cover of the minimum thickness needed for a water seal. This cover is about one-fifth the thickness of the conventional quarter wave cover.
We have used two sets of "thick" (3/8 inch) tires. One set is made from soft rubber and the other is made from a harder polyurethane. There are advantages and disadvantages for each type. The "soft" tires are similar to the soft rubber that is used for soft platen caliper and for the transducers used in the IPST laboratory instrument for ZD measurements. Soft rubber is believed to be desirable for coupling ultrasound to paper for longitudinal ZD measurements. However, the soft tires are more susceptible to distortion as speed is increased.

The "hard" tires are quite stiff and any out-of-roundness will cause a variation in pressure on the paper being measured and make it more difficult to hold the variation of distance between wheel axles at a minimum. On the other hand, the hard tires do provide good signal strength, do not distort at higher speeds, and would be expected to wear better in use.

The ZD measurement system must be capable of measuring ZD pulse flight times through paper with nanosecond accuracy. A number of techniques have been developed to compensate for the effects due to ambient temperature changes and to physical limitations of the measurement apparatus itself.

Because a temperature increase of one degree Centigrade in the fluid (water) increases the pulse propagation velocity by 2.4 meters/sec, an effective method for temperature compensation was developed. This method involves using an acrylic rod as a delay line or "shim" butted against the transmitter surface. The time of flight within the shim is proportional to the shim temperature. Since the shim temperature is equal to the fluid temperature, the shim flight time is used to determine the corrections required to compensate for changes in fluid temperature.

Some of the pulses critical to ZD velocity measurement may be very weak and degraded substantially by noise. The noise is effectively overcome by averaging a number of pulse sets produced by a train of excitation pulses sent to the transmitter. Additionally, second order interpolation and cross correlation are employed to measure pulse flight times with great accuracy. In fact, a digitization rate of only 50 nanoseconds/point can yield time measurements accurate to within a single nanosecond when second order interpolation is used in conjunction with cross correlation. The low digitization rate also allows extremely fast averaging (approximately 500 pulse sets averaged per second). This is important, because small but significant variations in tire thickness lead to corresponding variations in pulse flight times. In order to eliminate these variations, pulse sets are averaged while the tires turn exactly one or two
A square wave generator produces a continuous train of pulses. These pulses are fed to the input of a 3-channel analog multiplexer. A 4-state roll-around counter determines which multiplexer output is addressed to the input. The counter is clocked each time a metallic target, fixed to the transmitter tire, moves into the immediate vicinity of an inductive proximity sensor. One of the multiplexer outputs is coupled to the trigger input of a pulse/echo box. This device has a dual-purpose I/O line which outputs a short-duration ultrasonic pulse in response to an external trigger, then changes state to act as an input, accepting ultrasonic echo pulses and enabling the transmitter to be a receiver as well. The echoes are available at the box’s signal output line. The pulse/echo box is incorporated into the design in order to capture the pulse that propagates from the transmitter/shim boundary, reflecting back from the shim/water boundary to the transmitter for the purpose of the temperature compensation mentioned above. The multiplexer/counter arrangement passes triggers to the pulse/echo box during every 4th rotation of the transmitter tire, leaving 3 "dead" count states available for wave transfer, cross correlation and preparation for the next acquisition. The computer monitors the count state in order to synchronize acquisition and GPIB communication with tire rotation.

We have found that the force provided by the air cylinders, used to extend and retract the wheels, is not sufficient to maintain a fixed axle distance with "stiff" or out-of-round tires. Since small changes in transducer separation distance can affect flight time measurements, an inductive distance measurement circuit has been added to the system. A conductive (metal) target is attached to the support of the transmitting tire and an inductive sensor (Kaman Instrumentation Corporation) is attached to the support of the receiving tire. This circuit is insensitive to the presence of paper between the target and sensor. The circuit is calibrated in volts versus distance between the inductive sensor and the target. Readings from the circuit provide repetitive corrections for variation in the transducer separation distance, increasing the accuracy of the calculated velocities.

Initially, pulses taken during the measurement process were cross correlated against corresponding reference pulses taken without the presence of the paper web. As the accuracy of the measurements were improved, it became apparent that the time between trigger arrival at the oscilloscope and the onset of digitization contains a small degree of unpredictability. This "trigger jitter", though always less than the digitization period of the acquisition, is significant for the chosen 50 nanoseconds/point digitization rate. Fortunately, the time between points of
a digitized waveform is free of the jitter. By cross correlating only pulses from the present
acquisition, the problem of trigger jitter is overcome. This necessitates a different choice of
pulses for cross correlation, since stored reference pulses cannot be used.

For the shim flight time used in temperature correction, the pulse that reflects from the
shim/water boundary and back to the transmitter (w_pe) is cross correlated against the pulse that
reflects back from the transmitter face to travel through the shim and back a second time
(w_pe1). More precisely, since w_pe1 is inverted relative to w_pe, w_pe1 is negated before
cross correlation. The cross correlation gives the travel time within the shim (t_pe_s) without
trigger jitter.

In a manner similar to the above, trigger jitter is eliminated from the measurement of
change in transit time from transmitter to receiver with and without a paper sample between the
wheels. The primary pulse (w_1) is cross correlated with the echo pulse (w_pe), first without
a sample for a reference value, and then with the sample. The difference in these values
(t_pe_1_del) is then used to determine the ZD transit time through the paper.

\[
\text{del_ts} = \text{t_pe_1_del} + \text{del_d} / f_{\text{vel}}
\]

Where del_ts is the transit time through the sample, del_d is the thickness or caliper of
the sample, and f_vel is the effective fluid velocity.

The caliper, del_d, may be determined by cross correlating pulses w_1 and w_4,
represented by t1 and t2, without a sample and then cross correlating the same pulses with a
sample, represented by t1' and t2'. The caliper is then calculated

\[
\text{del_d} = \left[ (t2 - t1) - (t2' - t1') \right] f_{\text{vel}} / 2
\]

A digitizing oscilloscope (LeCroy 7200) performs the pulse acquisition and averaging.
The scope must be instructed by the computer to send its averaged waveforms over the GPIB
interface bus to the computer, which interpolates and cross correlates the waveforms, determining
the respective pulse flight time measurements. These are then used in the calculation of caliper
and ZD velocity, as described above.

Moving web measurements have demonstrated the reproducibility of the ZD measurements
with moving belts of paper. Rolls of paper representative of a variety of commercial grades have
been measured in the reel-to-reel mode on the web handler. The measurements are in general
agreement with laboratory instrument data for samples of these rolls.

**Discussion of Recent Results - ZD Measurements**

A web caliper measurement is required to calculate the out-of-plane (ZD) velocity of ultrasound through the web. We have demonstrated the use of the multi-reflected pulses described above to determine the web caliper. However, an independent caliper measuring instrument may be used in conjunction with the fluid-filled wheels. Potential advantages are: the transducer and shim positioning in the tires is less critical because one does not need to be concerned about reflected pulse overlap and interference; sampling rate may be increased because the amount of data to be transferred and cross correlated is reduced; the multi-reflected pulse is weak and more difficult to use as sample thickness increases; and the temperature sensitivity of the multi-reflected pulse time requires careful correction. Potential disadvantages of using a separate caliper gauge are: the sample locations at which the transit times are determined are not exactly the same as those for thickness measurement; the compression of the sample for transit time and thickness measurement will not be the same; and the caliper gauge will give a "hard platen" caliper whereas the wheels with soft rubber tires will be essentially a "soft platen" caliper.

We have mounted a Measurex contact caliper gauge on our test stand in line with the fluid-filled wheels. The measurement results obtained are in reasonable agreement with the ZD data determine with the multi-reflected pulse or the laboratory ZD instrument. The free run (not controlled by integral tire revolutions) sampling rate is approximately 4 seconds per 500 average sample versus 5 seconds per sample if caliper is determined with multi-reflected pulse in the fluid-filled wheels.

With an endless belt of paper mounted on the web handling system in the laboratory, we have demonstrated the feasibility of measuring the ZD ultrasound velocity with paper webs moving at web speeds up to 2000 feet/minute for several hours.

An invention disclosure was prepared and processed. A patent application entitled "OUT-OF-PLANE ULTRASONIC VELOCITY MEASUREMENT" was filed November 3, 1992.
BIMORPH TRANSDUCERS FOR IN-PLANE MEASUREMENTS

Review of Past Project Activity - In-plane Measurements

The in-plane measurement system is based on a set of wideband bimorph bender ultrasonic transducers excited at 80 KHz. These are similar to those developed for in-plane measurements in the laboratory instruments. A technique was developed to adhere a metal wire or cap to the tip of the transducer to provide a more durable wear surface. The transducers are mounted in the surface of a 10 inch diameter aluminum cylinder or drum in special spring-loaded holders. The drum surface has a grooved pattern intended to allow strong, narrow acoustic pulses in the plane of the paper. Provision is made in the web handling system to mount this drum. The transducers are oriented outward so that each active element protrudes slightly outside the circumference of the cylinder.

The transducers are used in sets of three. One transducer serves as a transmitter, and may be positioned at either end of the set or in between the two transducers used as receivers. The transducers may be oriented and aligned to operate in the longitudinal or shear mode in the MD or CD directions. For example, a transmitter positioned to excite longitudinal waves in the MD direction of the web also excites shear waves in the CD direction. Four transducers may be positioned relative to this transmitter into two sets of receivers. For both sets, the receivers are positioned at different distances (NEAR and FAR) from the transmitter in order to create a path length difference from transmitter to receivers. This path length difference is divided by the continuously measured difference in pulse flight times for the calculation of in-plane velocities.

One receiver set is aligned in the CD direction and oriented to transmit and detect CD shear waves. The CD NEAR distance is 46 mm and the CD FAR is 82 mm for a path length difference of 36 mm. The other set is aligned in the MD direction and oriented to transmit and detect MD longitudinal waves. The MD NEAR distance is 66 mm and the MD FAR is 200 mm for a path length difference of 134 mm. Similarly, one may orient the transducers to make longitudinal measurements in the cross direction and shear measurements in the machine direction.

The web is wrapped part way around the cylinder. The portion of a rotation within which a set of transducers are in contact with the web is the active measurement period for that set. During this active period, the transmitter is excited by a continuous stream of single-cycle
ultrasonic pulses spaced at approximately 1 millisecond intervals. The pulse interval is just long enough to allow time for the waves propagating within the web from the previous excitation to die out. Each excitation causes the transmitter to ring for a few cycles, producing in-plane waves that propagate in all directions. The receivers convert the waves back into electrical signals which are captured by a digitizing oscilloscope. After averaging a number of waves within the active period of rotation, the oscilloscope takes time measurements of corresponding half cycle peaks. The peak times for each receiver set are subtracted and sent to the 486 computer for velocity calculations.

The method used for passing excitations to the transmitter only during the active measurement period is similar to that incorporated into the ZD measurement system described earlier. A square wave generator sends a continuous train of pulses to the input of a 3-channel analog multiplexer. A 4-state roll-around counter determines which multiplexer output is addressed to the input. Two metallic targets are fixed to the cylinder. One target is positioned at the beginning of the active region to trigger an inductive proximity sensor, which clears the multiplexer/counter circuit. The other target, located at the end of the active region, clocks the counter. Excitation pulses are passed by the multiplexer to the transmitter only during the zero state of the counter. Thus, 80 KHz one cycle sine pulses are sent to the transmitter only while the transducers are in contact with the web. The signals detected by the 4 receiver transducers are captured and processed by a 4-channel digitizing oscilloscope.

The transducer housing and the carrier for mounting the transducers in the drum were redesigned. New transducers and carriers were made and mounted in the drum. Part of the housing is square in cross section and slides freely in a square hole in the carrier. This maintains the rotational orientation of the bender. Relatively weak springs hold the transducer in light contact with the paper sample or with the cap on the carrier when there is no paper. The spring loading is designed to minimize variation in the contact force between the transducers and the web. The caps are held in place with screws and can be removed to replace or reposition the transducers from outside the drum without removing the main body of the carrier.

In-plane CD shear and MD longitudinal data have been taken on rolls of paper representing a variety of commercial grades. These paper grades have included: 26, 42, and 69#/1000 sq.ft. liners; 30#/3000 sq.ft. newsprint, 26#/1000 sq.ft. medium, 70#/3300 sq.ft. coated 2 side free sheet, stamp paper with glue applied, and 60#/3000 sq.ft. extensible sack kraft. The data is in general agreement with cut samples measured with the laboratory in-plane ultrasonic
With the new carriers and transducers, one transducer set was positioned to measure in the CD longitudinal mode and another set in the CD shear mode. Data was collected with the web in light tangential contact with the drum and compared with data taken with the web wrapped part way around the drum. The results were essentially the same. With tangential contact only one longitudinal pulse set and one shear pulse set are captured each drum revolution, whereas with partial wrap the transducers are in contact with the web long enough to permit measurement by averaging several pulses each drum revolution.

Provision is included in the drum to mount transducer sets at plus and minus 45 degrees to the machine direction in addition to the web's machine and cross directions. Two sets of transducers were mounted at \( \pm 45 \) degrees and oriented to operate in the longitudinal mode. This transducer arrangement was used to take data on various rolls of paper, including a six section roll of three different 42# liners, a 69# liner, and a 26# medium.

These two measurements at \( \pm 45 \) degrees are not sufficient to determine the polar angle (the angle of the direction of maximum stiffness relative to the MD), but do provide an indication of the in-plane stiffness alignment relative to the machine direction. The squared velocity ratio, \( \text{sqr}((\text{Vel}+45)/(\text{Vel}-45)) \) or the difference divided by the average, \( 2[\text{sqr}(\text{Vel}+45) - \text{sqr}(\text{Vel}-45)]/[\text{sqr}(\text{Vel}+45)+\text{sqr}(\text{Vel}-45)] \) may be used to infer the direction of maximum stiffness relative to the MD.

**Discussion of Recent Results - In-Plane Measurements**

In-plane polar specific stiffness measurements are now routinely performed on cut samples in the laboratory, wherein velocity readings are recorded at every 5 or 10 degrees. The polar stiffness plot is normally in the shape of a peanut, but may be closely approximated by an ellipse at angles away from the vicinity of the CD. Since any ellipse may be uniquely defined by three distinct points, two points at \( \pm 45 \) degrees and one point in the MD (zero degrees) are sufficiently removed from the CD to define an ellipse. This ellipse provides a good approximation to the standard polar test for both polar angle and area. This was demonstrated by hand positioning a cross-reel strip (42# liner) over the in-plane drum and recording the MD and \( \pm 45 \) degree data at 2 inch intervals. This illustrates the type of data that could be obtained with on-line implementation.
The cylinder described above depends upon partial wrap and friction contact with the web in order to move at web speed. A system which would drive the above cylinder at web speed would have advantages over a friction driven system. A synchronous system would place no inertial load on the web. Therefore, it may be useable with very thin papers. In addition, transducer life should be much longer, since the transducers would not be abraded by a possible web-to-transducer speed difference.

**Synchronously Driven Wheels**

The cylinder system with a partial wrap is appropriate for use with narrow webs. However, this system would not be useable in a scanning system for wider webs. The partial wrap system would be limited to applications where it is practical to use multiple transducer sets in a cylinder with a length greater than the width of the web. The following describes apparatus which provides the required interface of the transducers to a moving web in an embodiment suitable for scanning across a wide web.

This system, designed for scanning across wide webs, includes three wheels, nominally 25 mm wide and 160 mm in diameter. The three wheels are positioned to contact the web tangentially, with two wheels placed above or on one side of the web and the third wheel placed below or on the other side of the web. The contact point of the third wheel is in line and preferable between the contact points of the two wheels above the web.

Each of the transducer wheels is driven by a servo motor and control system to maintain rotational synchronization of the wheels. An encoder is used to measure the speed of the web as input to the control system to match the speed of the transducer wheels to the speed of the web.

Two wideband bimorph bender ultrasonic transducers, the same or similar to those described above, are mounted in each wheel in special spring-loaded carriers. The transducers are mounted 180 degrees apart within each wheel, with one transducer oriented to produce/receive longitudinal waves in the direction of rotation (MD) and the other oriented for shear waves. The transducers are mounted so that each active element protrudes slightly outside the circumference of the wheel. The spring loading is designed to minimize the variability in the contact force between the transducers and the web.
Essentially, only the active elements of the transducers contact the web. This avoids the possibility of interference from ultrasonic pulses traveling from transmitter to receivers by paths other than through the paper web.

The synchronous system may be mounted on an O-frame or C-frame instrument platform, enabling cross-direction scanning -- something not possible with a wrapped cylinder. Provision may be made to bring the transducers into or out of contact with the web by an appropriate extension/retraction mechanism. This permits the system to be scanned over the web from an off-web position, and then extended to contact the web with the wheels rotating at web speed.

The drive system functions such that the longitudinal-oriented transducers in the three wheels are in contact with the web simultaneously during rotation, and the three shear-oriented transducers are in contact simultaneously one-half rotation later. The drive system matches the speed of the web without loading the web.

The above configuration has several advantages over the Microscan Sensor described by David W. Vahey [Tappi J. 70(3);79(1987)]. First, wideband, bender transducers rather than the larger 1 inch x 0.25 inch resonant transducers (U.S. Patent No. 4,713,572) are used here. The Microscan Sensor makes tangential contact from one side of the web. This causes a deflection of the web from the pass line, and it is particularly difficult to maintain good contact as web tension decreases near the edges. In our configuration, the pass line is maintained by having wheels on both sides of the web. The Microscan Sensor measures the CD longitudinal velocity and the CD shear velocity and calculates the MD longitudinal velocity, using the relationship:

\[ V_{md} = 2.58 \sqrt{V_{sh}}/V_{cd}. \]

Since the shear velocity \((V_{sh})\) should be the same whether measured in CD or MD, we measure both the longitudinal velocity and the shear velocity in the MD and using the same relationship calculate the CD longitudinal velocity. The CD span of the transducers in the Microscan Sensor is 10.5 inches. Thus a narrow moisture or basis weight streak would be averaged over this distance, whereas our configuration would be sensitive to CD variations with higher resolution.
An alternate configuration would be to replace one of the wheels with a wider aluminum cylinder; or, preferably, add two wheels to the shaft of one of the wheels. Two sets of three transducers could then be aligned on opposite sides of the cylinder or wheel set. These would allow cross-direction (CD) shear and longitudinal measurements similar to the Microscan Sensor. But, in addition, MD longitudinal and shear velocities could be measured, and the web pass line is maintained while scanning.

A third configuration would make use of the results that have been demonstrated in the laboratory with the cylinder-mounted transducer system described above. This configuration would provide on-line determinations of the in-plane polar specific stiffness. Measurements in three directions, two points at ±45 degrees and one point in the MD would be used to determine an ellipse which would provide an approximation to the standard polar plot.

Implementation for on-line measurements would involve the cylinder or wheels mentioned above, with the added transducers oriented at 45 degrees to the MD. A transmitter on the lower wheel would be positioned such that the angle between it and each outer transducer would also be ±45 degrees. These two angular measurements and the MD longitudinal measurement would determine three points to define an ellipse. This would allow nondestructive, on-line determination of polar stiffness values, such as, polar angle and area.

The synchronous "three-wheel" configurations described above continues the use of transducers in sets of three. This provides velocity measurement by determining the transit time difference over different distances. It may be appropriate to simplify the hardware required; for example, no transducers in the bottom wheel. The system would then use transducers in sets of two (transmitter and receiver). A technique to calibrate for time delays in the circuitry would be required. The tradeoffs involved remain to be explored.

An invention disclosure was prepared and processed. A patent application entitled "IN-PLANE ULTRASONIC VELOCITY MEASUREMENT" was filed November 3, 1992.
SUMMARY OF ACCOMPLISHMENTS:

1. An acrylic delay line or "shim" provides a means to sense temperature changes in the wheels and to correct the data for changes in temperature during a run.

2. The use of a pulse echo driver provides "shim" time data independent of the sample.

3. The use of a pulse echo driver also provides the basis for capturing pulses without scope jitter.

4. Data processing techniques determine the time differences of ZD pulses to within a single nanosecond.

5. Fast averaging for integral rotations of the wheels compensates for variations in the thickness and roundness of the tires.

6. The use of an independent caliper measuring instrument in conjunction with the fluid-filled wheels reduces data processing required.

7. The feasibility of measuring the ZD ultrasound velocity with paper webs moving at web speeds up to 2000 feet/minute has been demonstrated.

8. Both ZD and in-plane ultrasound velocity data have been collected on a variety of commercial paper grades.

9. New in-plane transducers and carriers provide improved reproducibility in the coupling of the transducer to the paper web.

10. Various combinations of MD and CD shear and longitudinal velocity measurements have been made with drum mounted in-plane transducers.

11. Measurements at plus and minus 45 degrees have been demonstrated as a measure of the orientation of in-plane stiffness relative to the machine direction.

12. A new concept has been designed for mounting in-plane transducers in a configuration
13. Two patents applications were filed November 3, 1992.

14. Commercialization discussions and planning have been initiated with a control instrumentation vendor.
GOALS FOR FY 93-94:

1. Establish working relationship with vendor of instrumentation and control systems for paper machines.

2. Obtain paper company participation in providing host mill test site.

3. Build and test new concept for in-plane sensors which can be scanned and provide an on-line measure of the modulus polar angle.

4. Incorporate vendor data collection and processing hardware, software and procedures where feasible.

5. Evaluate vendor-compatible in-plane prototype on web handling system at IPST.

6. Install and test prototype in-plane instrumentation on a paper machine at a host mill test site.

7. Initiate ZD fluid-filled wheel system development with vendor, improve wheels and use vendor electronics.
ZD Ultrasonic Averaging Measurement System

Square Wave Generator
5 V, 1 KHz

Clock

4-State Roll-Around Counter

A1
A2
A3

+5 V
(TTL High)

3-Channel Analog Multiplexer

B1
B2
B3

Pulse / Echo Box
Signal Out

Trigger
Pulse/Receive

Inductive Distance Measurement System

40 dB Preamp

Digital Voltmeter

Parallel I/O Port

386 Computer

GPIB Interface

Ch1 External Trigger

Ch2 Digitizing Oscilloscope
2-26 2.92 -> 1 Rev Avg, Multi-Sec Reel

ZD data. Thickness determined by MX caliper gauge. Six section roll; 42# Liner(A), 42# Liner(B), 69# Liner, 42# Liner(C), 26# Medium, 42# Liner(A).
ZD data. 42# Liner Belt at 2000 feet/minute. Thickness measured with MX caliper gauge.
In-Plane data. Longitudinal velocity measured at +45 degrees to MD (top) and -45 degrees (bottom). Six section roll; 42\# Liner(A), 42\# Liner(B), 69\# Liner, 42\# Liner(C), 26\# Medium, 42\# Liner(A).
In-plane data. Ratio of longitudinal velocities measured at plus and minus 45 degrees to MD for six section roll: 42# Liner(A), 42# Liner(B), 69# Liner, 42# Liner(C), 26# Medium, 42# Liner(A).
4.23.92 -> Polar Angle from 45 Deg Ellipse Calc

Polar Angle (Degrees)

CD Strip Position (Inches)
FUNDAMENTALS OF ACOUSTIC RADIATION PRESSURE EFFECTS ON WET FIBERS

STATUS REPORT

FOR

PROJECT 3767

April 29, 1993
Institute of Paper Science and Technology
Atlanta, Georgia
PROGRAM OBJECTIVE:

To explain acoustic radiation force and torque effects on fluid suspended fibers and to develop novel ultrasonic techniques aimed at evaluating physical properties of fibers and manipulating fiber suspensions.

RATIONALE:

When subjected to acoustic radiation force and torque in a standing ultrasonic wave field, water suspended fibers migrate and reorient toward stable equilibrium spatial and angular positions, respectively. These phenomena are described as acoustic migration, agglomeration or layering, and acoustic reorientation or alignment, respectively. Since fibers can be manipulated without any mechanical contacts, acoustic radiation pressure effects could provide powerful tools for process control. Applied to single fibers and combined to optical detection techniques, they have the potential for simultaneous on-line characterization of physical properties such as wet fiber flexibility, length and coarseness. It might also be possible to achieve virgin/recycled furnish identification. Applied to fiber suspensions, acoustic force and torque effects have the potential for the development of advanced techniques such as acoustic harvesting/separation of fibers (and other particles), and monitoring of fiber compactibility. They might be the basis for the development of novel forming and fine-tuning alignment technologies. The project is centered around the use of one-dimensional and two-dimensional acoustic resonators mounted in a flow loop.

SUMMARY OF FY 92-93 RESULTS:

- A contract was awarded to a consultant in ultrasonics for the design and construction of prototype acoustic resonators and special flow loop elements. The first resonator was received in January 1993. Preliminary measurements will be performed as soon as a special supporting structure is completed.

- A numerical analysis of fiber flexibility in the anti-nodal planes of a plane standing wave field was undertaken. Preliminary results obtained with a simplified model of single-fiber bending indicate the feasibility of the proposed concept.

- The design of an appropriate experimental setup to study acoustic force and torque effects is well underway.

- A research proposal related to the fundamental study of fluid suspended rigid and flexible fibers in a standing ultrasonic wave field is under preparation.
1. PROJECT OBJECTIVES

The scientific objectives of the project during the next three years are as follows:

1. To explain the translational and rotational motion of rigid and flexible fibers subjected to one-dimensional (1-D) and two-dimensional (2-D) plane standing wave fields in a quiescent fluid;
2. To explain the motion of normally moving rigid and flexible fibers in 1-D and 2-D plane standing wave fields, at low Reynolds numbers;
3. To elucidate the physical rules governing acoustic reorientation at the expense of acoustic migration and vice-versa;
4. To determine the relationship between a distributed load (acoustic force) and the lateral deflection of a flexible structural beam (fiber) at acoustic equilibrium.

2. INTRODUCTION

When subjected to a plane standing wave field, fluid suspended fibers shorter than one-fourth of the acoustic wavelength migrate to preferred sites at stable equilibrium positions and reorient to stable equilibrium angular positions. The suspension takes on a striped appearance and regions of increased fiber concentration alternate with regions of decreased fiber concentration. This migration phenomenon is a consequence of the acoustic radiation force. Not as clearly distinguishable, the reorientation process is due to the acoustic radiation torque: fibers rotate in such a way that their axis of symmetry becomes parallel to the agglomeration planes. Both acoustic force and torque are non-linear effects.

Since the pioneering work of King about acoustic radiation pressure effects on spheres and oblate spheroids [1,2,3], numerous theoretical and experimental studies (not listed here) have been reported on these particles in gases and liquids. Surprisingly, this is not the case for prolate spheroids, partly due to the complex geometry of these particles, and partly due to the lack of practical interest for such particles interacting with a sound field. Awatani was the first to calculate the acoustic force on a prolate spheroid [4] and a rigid cylinder [5], in plane progressive and standing wave fields. He found that the force on a prolate spheroid whose axis of symmetry is perpendicular to the sound field direction (stable orientation), is larger than that on a disc or a sphere which has the same projective area. Using a method first developed by Westervelt [6], Dysthe showed that the acoustic force on a non-spherical body depends on its orientation relative to the sound field direction [7]. Recently, Zhuk [8] and Wu et al. [9] reported independent derivations of the acoustic force on a rigid cylinder at stable orientation, in plane progressive and standing wave fields, respectively. In addition, Wu et al. examined the acoustic force on a water
suspended glass microneedle in a standing wave field [9]. Hasegawa et al. [10] derived an expression for the acoustic force experienced by an elastic cylinder in a plane progressive wave field. While Maidanik [11] studied the acoustic radiation torque in general, an expression describing the acoustic force on a cylinder is not yet available. Putterman et al. [12] derived a best-fit equation to predict the torque on a levitated cylinder positioned in a loop. Water suspended flexible fibers (wood pulp fibers) subjected to a plane standing wave field were recently investigated [13-17], and a correlation was found between the average fiber length and the forward-scattered light recorded during acoustic excitation [16,17]. Wang and Micko [18] used a standing wave field to agglomerate wood fibers in fiber slurries.

Trajectories of small spherical particles moving under the effect of gravity, viscosity and radiation pressure, in a plane standing wave field oriented horizontally, were analyzed by King [1]. Gould and Coakley [19] and ter Harr and Wyard [20] investigated the translational motion of particles in the absence of gravity and viscosity. Using a similar approach, a preliminary study of the translational and rotational motion of fibers in a plane standing wave field was reported by Brodeur [21]. This analysis indicated that migration and reorientation phenomena are dominant effects for long and short fibers, respectively. The motion of a rigid cylinder due to a plane elastic wave was studied by Miles [22]. In a related subject, effects of particle shape and orientation on the propagation of sound in suspensions were investigated by Ahuja and Hendee [23].

From the literature survey, it appears that the behavior of moving cylindrical particles subjected to a sound field whose direction is perpendicular to the shear flow direction has not been studied. Acoustically-induced lateral deflections of flexible structural beams (e.g. wood fibers) have not been investigated.

3. THEORETICAL BACKGROUND

Acoustic Migration

Consider a fluid suspended rigid circular cylinder interacting with a plane standing wave field as shown in Figure 1. The acoustic wavelength is defined as λ. Nodal planes at zero particle velocity are located at x = h_N = nλ/2, n = 0, ±1, ±2 ..., and anti-nodal planes or loops (L) are situated at x = h_L = (n + 1/2) λ/2, n = 0, ±1, ±2 .... Neglecting the presence of gas bubbles, temperature effects, wave distortion (Oseen effect) [24] and buoyancy forces, the cylinder with radius a and length ℓ >> a and << λ/4 reacts to forces and torques due to acoustic radiation pressure and viscous drag. The pressure force of the sound field is given by
where \( \vec{e}_r \) is a unit vector normal to the surface \( S \) of the cylinder and \( p \) is the pressure intensity, which is described as [1]

\[
p = p_0 + \rho_0 \dot{\phi} + \frac{1}{2} \rho_0 c^2 \dot{\phi}^2 - \frac{1}{2} p_0 (\vec{\nabla} \phi)^2
\]  

in which \( p_0 \), \( \rho_0 \) and \( c \) are the suspending medium static pressure, equilibrium density and sound velocity; \( \phi \) is the velocity potential. On the theoretical [7] and experimental [21] basis that the cylinder rapidly finds the stable equilibrium orientation on the onset of acoustic excitation, its axis of symmetry is preferentially oriented perpendicularly to the standing wave field direction (x-axis) during migration. In this situation, the analytical result developed by Wu et al. [9] for the case of a unit length circular cylinder in a plane standing wave field is

\[
F_{sw} = f(\beta) \frac{\pi a^2}{2} E k \sin[2k h]
\]  

where \( f(\beta) = \left[ \frac{2(1-\beta)}{(1+\beta)} \right] + 1 \) is the inertia factor;
\( \beta = \rho_0/\rho_1 \) is the ratio of the suspending medium density to cylinder density;
\( k = 2\pi / \lambda \) is the wavenumber;
\( E = (\rho_0 c)^2 / (2p_0) = \rho_0 (k \phi)^2 / 2 \) is the mean energy density;
\( h \) is the cylinder center of mass position with respect to a nodal plane.

Eq. 3 indicates that \( F_{sw} \) is maximum halfway between nodes and loops and inversely proportional to the acoustic wavelength. Also it specifies that the larger the cylinder radius, the larger the acoustic force. Providing that \( \beta \) is less than 3, which is the case for a solid cylinder in a fluid, \( f(\beta) \) is positive and so is \( F_{sw} \). Thus, migration is toward the nearest loop at stable acoustic equilibrium.
Now, taking into consideration a Newtonian fluid with viscosity $\mu$ and the Oseen's approximation to the Navier-Stokes equations at low Reynolds numbers, the drag force past a unit length circular cylinder of radius $a$ is [25]

$$F_d = \frac{4 \pi \mu}{S} \frac{v(h)}{S}$$

(4)

where $S = \frac{1}{2} - \gamma + \ln[8/R]$ in which $\gamma$ is Euler's constant and $R = \rho_0 (2a)v/\mu$ is the Reynolds number; $v(h) = dh/dt$ is the cylinder migration velocity. The equation of motion is described as

$$m_c \frac{d^2 h}{dt^2} = F_{sw} - F_d$$

(5)

where $m_c$ is the cylinder’s mass. The migration velocity is easily obtained for the case where $k << 4 \pi \mu / (S m_c)$, i.e., when the acceleration is neglected:

$$v(h) = \frac{f(\beta) a^2 S \bar{E} k}{8 \mu} \sin[2k h]$$

(6)
Acoustic Reorientation

The acoustic radiation torque acting on a rigid cylinder in a plane standing wave field originates from the acoustic force gradient denoted between nodes and loops. Referring to Fig. 1, the rotation axis is the y-axis for a cylinder lying in the x-z plane. The rotation angle $\theta$ is defined as the angle between the standing wave field axis and the normal to the cylinder axis of symmetry. According to King [3] and Putterman et al. [12], the torque acting on a non-spherical object in a standing wave field is proportional to its volume and the mean density of acoustic energy. King [3] has shown that the couple on a thin circular disc ($k a << 1; a$ is the disc radius) situated in a node is of a much smaller order of magnitude than that exerted on it in a loop, and it is of opposite sign. Assuming a similar reasoning for a cylinder, the torque for a cylinder located at position $h$ is

$$T_{sw} \propto -\pi a^2 \ell \sin[2\theta] \sin^2[kh]$$

(7)

It is negative with respect to $\theta$ and its magnitude increases as a function of $h$. The stable equilibrium orientation is at $\theta = 0$. When positioned at $h = h_L$, the cylinder is at a stable equilibrium spatial position and cannot rotate. Hence, it should be in a levitation state. Using Eq. 4, one gets an approximate expression for the drag torque acting on a cylinder of length $\ell$

$$T_d \propto \mu \ell^3 \omega(\theta)$$

(8)

Neglecting cylinder inertia and equating Eqs. (7) and (8), the cylinder reorientation velocity is proportional to

$$\omega(\theta) \propto -\left(\frac{a}{\ell}\right)^2 E \sin[2\theta] \sin^2[kh]$$

(9)

This equation has not been verified experimentally.

Distribution of Cylinders in a Plane Standing Wave Field

Consider a dilute suspension of cylinders, i.e., when the fraction of the total volume of the suspension occupied by the cylinders is less than $(2a/\ell)^2$. If one neglects viscosity, gravity and interactions between cylinders, it is relatively easy to evaluate the distribution of cylinders between $h_N \leq h \leq h_L$ as a function of time (see Fig. 1). Using the continuity equation,
in which \( f(x,t) \) is a continuous distribution, one gets upon substitution of Eq. 6 and after integration:

\[
f(h,t) = \frac{f_0}{\sin^2[kh] \exp[-2Ct] + \cos^2[kh] \exp[2Ct]} \tag{11}
\]

Here \( f_0 \) is the initial cylinder distribution at \( t = 0 \) and \( C \) is a constant. A plot of \( f(h,t) \) for an arbitrary constant \( C \) is shown in Fig. 2. It is seen that as time increases, the distribution rapidly goes to infinity at \( t \) becomes large, indicating that all cylinders have completed their migration at \( h = h_L \). In practice, the distribution cannot go to infinity because cylinders have finite dimensions. Thus, Eq. 11 must be modified by assuming a discrete distribution of cylinders [21]. A similar treatment can be used to predict the angular distribution of cylinders as a function of time.

Figure 2. Three-dimensional plot of the one-dimensional continuous distribution function \( f(x,t) \). The zero position is at a nodal plane. Cylinders migrate toward the nearest loop plane.
**Fiber Flexibility**

Among pulp properties affecting both the process of papermaking and end-use properties of paper, wet fiber flexibility is of primary importance. As stated by Van den Akker [26] in his early physical analysis of paper fiber-fiber bonding, fiber flexibility plays a fundamental role in the forming, structure and properties of a sheet. For example, its effect on fiber orientation during formation is noteworthy because flexible fibers tend to react to the forming shear field by bending instead of rotating as stiff fibers would [27]. It is well known that beating and refining increase fiber flexibility; a larger flexibility index means a stronger sheet. While laboratory methods involving individual fiber or ensemble property measurements have been developed to investigate wet fiber flexibility [28-40], continuous monitoring of fiber flexibility during refining operations has yet to be demonstrated. It is hypothesized that wet fiber flexibility could be determined in a non-contact manner using a standing wave field.

**Fiber at Stable Equilibrium Orientation in a 2-D Plane Standing Wave Field**

Consider an horizontal system of two orthogonal plane standing wave fields with identical acoustic wavelengths. In this system, acoustic forces are horizontal, i.e. normal to gravitational forces. Now, consider a flexible but incompressible cylinder or structural beam located at the intersection of two orthogonal loop planes. If the cylinder is perfectly straight, the distributed acoustic loads acting on it are very weak because $h \rightarrow \lambda/4$ (see Eq. 3). Under such a case, the cylinder is in a state of stable equilibrium orientation (vertical) whatever the load intensities are. However, if the cylinder exhibits deformations along its axis of symmetry (e.g., curly fiber), it will be subjected to non-zero acoustic forces along each sound field direction. If the loads are weak and balanced (equal acoustic power), the deformed cylinder will simply stay at acoustic equilibrium. If the loads are unbalanced, the cylinder may rotate about its principal axis of symmetry to regain equilibrium. If the loads are sufficiently strong, bending moments may be induced along each sound field direction, leading to induced lateral deflections. These deflections are function of the flexural rigidity $EI$ of the cylinder where $E$ and $I$ are the Young's modulus and moment of inertia, respectively.

One can simplify the situation by assuming that the acoustic loads are unbalanced in such a way that one of the loads is large enough to stabilize the cylinder, thus preventing any rotation due to the second load which can be varied. In this situation, the 3-D deflection problem can be reduced to a 2-D deflection problem, and the lateral deflection distribution can be investigated along a single bending plane. This simplification is illustrated in Fig. 3. A deformed cylinder is
stabilized by an acoustic load applied along the y-axis. The bending plane corresponds to the x-z plane. The larger the distance between the neutral axis (z-axis) and a cylinder element, the larger the acoustic force (see Eq. 3). As indicated in the figure, the acoustic force per unit length of the cylinder can be decomposed into two components: a normal component, \( q(u) \), and an axial component, \( s(u) \); \( u \) is defined as the beam reference frame axis. Considering only the normal component and assuming that the cylinder follows Hooke's law, one can apply the relationship describing the bending moment of an elastic beam as a function of the distributed load \( q(u) \), i.e.,

\[
\frac{d^2 M}{du^2} = -q(u) \tag{11}
\]

The beam deflection \( v(u) \) as a function of the bending moment is

\[
\frac{d^2 v}{du^2} = -\frac{M(u)}{EI} \tag{12}
\]

Thus, the measurement of \( v(u) \) as a function of the acoustic load can be used to determine the flexural rigidity \( EI \). This method, which requires substantial refinements, remains to be demonstrated experimentally.
4. PROJECT DESCRIPTION

Experimental Methodology

Acoustic Resonators

In order to fulfill the goals of this project, it is necessary to have appropriate acoustic resonators that can be directly mounted in a small flow loop and used in a variety of ways. The design is not straightforward because we are looking for a modular construction, a rectangular geometry, a range of frequency not easy to deal with, and an excellent field uniformity. A schematic of the resonator concept is presented in Fig. 4. Nodal/loop planes are parallel to the flow axis which can be vertical or horizontal.

![Schematic of the prototype acoustic resonator.](image)

The transducer-reflector assembly forms a one-dimensional resonant cavity. The transducer is made of several layers of piezoelectric material. This sandwich arrangement is used to optimize thickness vibrations at the expense of lateral vibrations. The number of layers is inversely related to the resonant frequency. A graphite quarter-wave matching layer is used to optimize energy transfer between the transducer and the fluid. The reflector can be made of stainless steel or glass. The resonant length is set to 20 mm. Replacement of viewing ports (see...
Fig. 4) by a second 1-D resonator enables experiments to be performed in a 2-D plane standing wave field.

Resonators operating at 75 kHz, 150 kHz and 600 kHz are initially proposed. Corresponding quarter-wavelengths in water are 5 mm, 2.5 mm and 0.625 mm, respectively. These figures must be compared with the proposed fiber length range which is 0.1 to 5 mm. For experiments at low Reynolds numbers, the nominal resonator length (redefined as the acoustic dwell length) can be increased by mounting resonators in series. Integral hydrophones mounted on a stainless steel reflector will be used to monitor the acoustic power. A temperature compensation circuit will be used to stabilize the acoustic wavelength.

**Pumping System and Degassing System**

A variable and reversible flow pumping system will serve three purposes: to transport fiber suspensions in and out of the resonators for quiescent fluid studies, to levitate settling fibers against gravity, and to study fiber motion at low Reynolds numbers. Experiments will be carried on using glass fibers, rayon fibers and wood pulp fibers in water (see below). Since cavitation might be a problem at RF frequencies, a continuous flow ultrasonic degassing system will be integrated to the flow loop. Also, a constant temperature circulation system will be utilized to stabilize fluid temperature within ±0.01°C and to study temperature effects.

**Optical Inspection of Fiber Motion/Fiber Flexibility**

Assuming low consistency suspensions (<0.005%), it is proposed to characterize fiber motion using an argon-ion laser. Forward scattered light collected from thin sheets of light parallel to the agglomeration planes is an excellent indicator of translational motion [16]. Fiber rotation will be monitored through birefringence. Acoustically-induced lateral deflections of curly fibers will be monitored using a stereomicroscope and an image analysis system.

**Selection of Fiber Suspensions**

As length and coarseness of papermaking fibers are approximately related for a given wood species, it is not easy to distinguish aspect ratio effects. Hence, it is a prerequisite to make preliminary measurements with synthetic fibers of constant length and variable coarseness and variable length and constant coarseness. It is proposed to utilize glass and rayon fibers. Available deniers for rayon fibers are 1.5, 3, 4.5 and 5.5, and length figures will range from 0.2 to 5 mm.
Since kraft pulp fibers are considerably more flexible than TMP pulp fibers, these two types of pulp are suggested for flexibility analysis. Never-dried length classified and whole pulp samples will be tested.

*Computational Analysis of Fiber Motion and Flexibility*

This project is essentially experimental. However, in order to better appreciate and predict fiber motion and flexibility, it is necessary to develop appropriate models. Numerical modeling of fiber flexibility has already begun (see preliminary results below).

5. TASKS

The following tasks will be carried on during the next three years.

**Task #1: Fiber Motion in a Quiescent Fluid**

In agreement with the first objective, the translational and rotational motion of fibers will be studied in a quiescent fluid. Resonators will be mounted vertically in order to achieve horizontal fiber motion in the sound field. Relationships will be obtained between the acoustic wavelength, acoustic power, suspending medium viscosity, temperature and gas content, gravity, suspension consistency, and fiber aspect ratio, density and flexibility. Observation of fiber motion in a 2-D variable power sound field is of interest.

**Task #2: Fiber Motion at Low Reynolds Number**

Assuming that fiber motion is well understood in a fluid at rest, the analysis will be extended to include the trajectory of fibers interacting with a sound field at low Reynolds numbers. It is of particular interest to study the behavior of rigid and flexible fibers entering a 2-D standing wave field and observe their 3-D motion as a function of the acoustic wavelength, acoustic power and acoustic dwell length. Somehow, fiber motion will be sensitive to flexibility, which might provide an alternative to flexibility analysis at acoustic equilibrium. Exploratory experiments in the laminar regime will be performed to study shear force effects.
Task #3: Fiber Migration vs. Fiber Reorientation

Using the results collected during the first and second set of experiments, it is proposed to determine conditions for which fiber migration is a more efficient process than fiber orientation and vice-versa, especially in the creeping flow regime. In other words is it possible to decouple these phenomena?

Task #4: Fiber Flexibility Evaluation in a Quiescent Fluid

This task, which will be conducted in parallel to the previous tasks, involves the measurement of the flexural rigidity of fibers in a standing wave field. It is hypothesized that curly fibers (e.g., wood pulp fibers), which are at acoustic equilibrium in a horizontal 2-D plane standing wave field, can be deflected by the distributed acoustic load along one plane, providing that they are stabilized by a sufficiently large distributed acoustic load along the second bending plane. Preliminary calculations (see below) indicate that the acoustic force can be large enough to induce lateral deflections of wood fibers.

6. APPLICATIONS

Outcomes from this project might be the basis for the development of a whole new array of industrial applications and measurement techniques: fiber flexibility evaluation, fiber straightening process, fiber compactibility and conformability analysis, acoustic fiber orientation control, fiber/particle separation processes.

The contactless measurement of wet fiber flexibility has been so far the driving force for this project. Providing that acoustically-induced lateral deflections of wood pulp fibers can be demonstrated, the same technique could be applied to fiber suspensions in order to study fiber compactibility.

Apart from flow induced alignment methods which offer limited controllability, very few attempts have been made to actively control fiber orientation in fiber suspensions [41]. Since acoustic reorientation is a mechanical phenomenon, it can be applied to electrically neutral and non-magnetic fibers. One could envision alignment processes combining acoustic, and electric or magnetic methods.
Regarding acoustic particle separation and harvesting techniques, one notes a regain of interest in this area [42,43]. Acoustic agglomeration of dust particles in air has long been demonstrated. The novel methods are also devised around particle motion parallel to the acoustic field. However, they are aimed at separating particles according to their size. In the present scheme, in which the sound field is normal to the flow axis, one could take advantage of particle motion normal to the sound field. Spatial/angular rearrangement of fibers might be a possible application.

7. PRELIMINARY RESULTS

Numerical Modeling of Acoustic Fiber Flexibility

In order to demonstrate the feasibility of the acoustic fiber flexibility method, a preliminary numerical analysis of the problem was undertaken. A simple deformed beam structure (broken beam) was considered. It is shown in Fig. 5. This 2-D structure is assumed to be in acoustic equilibrium, i.e., located in the loop plane of a one-dimensional plane standing wave field. It is not allowed to rotate. Its length is \( \ell \). Left and right sections of the beam are at an angle \( \phi \) relative to the z-axis (sound field reference frame). In agreement with Eq. 3, it can be shown that the acoustic load as a function of the \( u \)-axis (beam reference frame - see Fig. 3) is:

\[
q(u) = F_{max} \cos(\phi) \sin[2 k \sin(\phi) \left( |u| - \ell / 4 \right)] , \quad -\ell / 2 < u < \ell / 2
\]

where \( F_{max} = (\pi a^2 \bar{E} k) / 2 \). A plot of \( q(u) \) is shown in Fig. 6. The following numerical values were considered:

\[
\begin{align*}
\ell & : \quad 2 \text{ mm (beam length)}; \\
a & : \quad 25 \text{ mm (beam radius)}; \\
\phi & : \quad 9 \text{ degrees (beam section angle relative to the z-axis)}; \\
\lambda & : \quad 625 \text{ mm (acoustic wavelength)}; \\
k & : \quad 1 \times 10^4 \text{ m}^{-1} \text{ (wavenumber)}; \\
\rho_0 & : \quad 1 \times 10^3 \text{ kg/m}^3 \text{ (density of water)}; \\
p_0 & : \quad 30 \times 10^5 \text{ Pa (static pressure)}; \\
c & : \quad 1500 \text{ m/s (sound velocity in water at room temperature)}; \\
EI & : \quad 10 \times 10^{-12} \text{ N-m}^2 \text{ (flexural rigidity for stone groundwood pulp fibers - see Ref. 34).}
\end{align*}
\]
Using Eq. 12, the bending moment $M(u)$ can be derived analytically. Boundary conditions are such that the shear force and bending moment are zero at $u = \pm \ell/2$ (note: left and right beam sections are considered cantilevers). The result is depicted in Fig. 7. Finally, one can use Eq. 13 to determine the deflection curve $v(u)$. In this derivation, it is assumed that the deflection angle and lateral deflection are zero at $u = 0$. These boundary conditions are somewhat unrealistic because they do not allow the beam to deflect at $u = 0$. To compensate for this difficulty, the deflected beam is repositioned thereafter in the sound field. This is shown in Fig. 8.

How realistic is this model? Assuming that all parameters but the static pressure are fixed, the deflection curve shown in Fig. 8 was obtained using a static pressure of $30 \times 10^5$ Pa. It is known from the work of Wu et al. [9] that a RMS static pressure of $1 \times 10^5$ Pa can be used prior to air bubble formation at the surface of the transducer or the reflector. Even though the pressure used in the model is 30 times higher, a $30 \times 10^5$ Pa pressure is not unrealistic. In the eventuality of air bubble formation, it is most likely that air bubbles will occur at the nodal planes rather than the loop planes because the density of air is less than that of water (see Eq. 3). Thus, air bubbles should not interfere with the observation of fiber deflection. However, this remain to be demonstrated experimentally. To avoid difficulties with air bubble formation, preliminary experiments will be conducted in degassed water.

A more advanced model, which would consider beam deflection without any fixed point, load variation as the beam is deflected, and a statistically variable initial beam shape, will be developed.

![Figure 5. Initial beam shape in the loop plane of a one-dimensional plane standing wave field (sound field reference frame).](image-url)
Figure 6. Normal acoustic load (beam reference frame).

Figure 7. Induced bending moment (beam reference frame).

Figure 8. Beam lateral deflection (sound field reference frame).
8. LITERATURE CITED
