INSTITUTE OF PAPER SCIENCE AND TECHNOLOGY

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FUNDAMENTALS OF ACOUSTIC RADIATION PRESSURE

Project F008

Report 1

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A Progress Report

to the

MEMBER COMPANIES OF THE INSTITUTE OF PAPER SCIENCE AND TECHNOLOGY

By

P.H. Brodeur

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PROJECT OBJECTIVES

- Investigate fundamentals of acoustic radiation pressure (ARP) effects on fiber suspensions;

- Investigate mechanisms of acoustic agglomeration and reorientation on fiber suspensions;

- Demonstrate the concept of acoustic wet fiber flexibility;

- Demonstrate the concept of acoustic fiber separation/fractionation;

- Explore other process-related applications of acoustic radiation pressure, acoustic cavitation, and acoustic streaming such as acoustic alignment of fibers, acoustic forming, acoustic refining, acoustic deinking, acoustic separation/fractionation of non-fiber particles;

- Determine the economic viability of acoustically-based industrial processes.

VALUE TO THE INDUSTRY

The basic idea of this project is to investigate the multiple uses of an ultrasonic field to manipulate fiber suspensions in a contactless manner. The long-term streamline is to come up with novel pulp and paper industrial processes that will fulfill the need for on-line adaptability to different furnishes and/or different products, and hence, considerably increase the return on capital investment. As an example, while current pressure-screen fractionators are dedicated mechanical systems, acoustically-based fractionators, which would be free of moving parts, would in principle be capable of processing in a continuous manner different furnishes or varying reclaimed fibers by simply controlling the acoustic power, the acoustic frequency, and the

acoustic dwell length. Moreover, one could envision that different fractionation needs could be addressed by simply resetting the acoustic parameters.

Since the general research area of cylindrical particles (fibers) interacting with an ultrasonic field has been largely unexplored, a great deal of attention must be devoted to the fundamental issues. More particularly, it is necessary to fully understand the mechanisms of acoustic agglomeration and reorientation for rigid and flexible fibers under different flow conditions.

PROJECT HISTORY

Project F008 was initiated in July 1992. In addition to the overall design of an experimental setup to study acoustic radiation pressure effects on fluid suspended fibers, the construction of a prototype acoustic cell was completed during the first year of activity. Its operating frequency is 150 kHz. Qualitative observations gathered using rayon fibers and wood pulp fibers were obtained. They indicated that the acoustic cell was working according to its specifications.

SUMMARY OF ACTIVITIES

From July 1993 to June 1994, the following activities were initiated and/or completed:

- ### ARP Experimental Setup

  The construction of an experimental setup to study various acoustic radiation pressure effects was initiated. Various components such as a peristaltic pump, a 400 W power amplifier, an ultrasonic degassing system, a temperature controller, a temperature circulation bath, a CW argon-ion laser were purchased. A custom-designed calibrated hydrophone was also purchased. The setup includes a flow system to transport fiber suspensions in and out of the acoustic cell. It can accommodate fiber consistencies up to 1%, under zero-flow and laminar flow conditions. Temperature and air content of the suspending medium (water) can be controlled. The argon-ion laser will be used as the main element in the yet to assemble optical monitoring system to quantify acoustic agglomeration and reorientation effects.

- ### Research Proposal Entitled: "Acoustic Fiber Fractionation"

  In response to a Notice of Program Interest from the Department of Energy, an elaborated proposal was completed in October to demonstrate the concept of acoustic fiber fractionation from laboratory- to pilot-scale level. The five-year project has four partners: IPST, Naval Research Laboratory, Black Clawson Company, and Sonic Concepts. The proposed separation method is based on the use of a high-power ultrasonic field.

- Investigation of Acoustic Wet Fiber Flexibility

  It has been proposed that an ultrasonic field could be used to determine the flexibility of wet fibers for on-line refining control. The investigation of acoustic wet fiber flexibility was begun in October by Mr. Troy Runge, a M.S. student at IPST. A research proposal was prepared. Phase I of the research program involves the demonstration of single-fiber deflection due to a distributed acoustic force. A 3-D translation system was added to the basic experimental setup to position fibers mounted as cantilever beams anywhere in the acoustic cell. The use of a CCD camera to detect fiber deflection was demonstrated. Qualitative observations were obtained using earlywood and latewood fibers (Loblolly Pine).

- Investigation of Acoustic Fiber Separation/Fractionation

  Mr. Kiet Ma, an IPST M.S. candidate, joined the research group in May to begin a preliminary investigation of acoustic fiber separation. In addition to the preparation of a research proposal, the design for a mechanical device to collect fibers separated by a traveling wave field was completed. The concept of fiber separation in a laminar flow is further described below.

- Minimization of Acoustic Cavitation

  Using the hypothesis that acoustic cavitation might be detrimental to acoustic agglomeration at sub-MHz frequencies, a theoretical analysis of the methods to reduce or eliminate cavitation (e.g., degassing, pressurization) was performed by Mr. Charles Chen, an IPST Ph.D. candidate. He pointed out in his report that the conditions to minimize acoustic

cavitation have not been systematically investigated. The report is available to IPST Member Companies.

ACOUSTIC FIBER SEPARATION IN A LAMINAR FLOW

Introduction

Separation of virgin or reclaimed wood pulp fibers into two or more fractions which are relatively enriched in longer or shorter fibers is an important step of the papermaking process [1-3]. Fiber fractionation allows an optimized use of raw materials, increases production versatility, and contributes to waste and energy consumption reduction. Typical examples are: optimization of multi-layered products by placing fractions where they are most needed in the sheet; energy savings by restricting pulp refining to the long-fiber fraction; separation of valuable fraction from waste.

Various technologies have been devised during the past forty years to fractionate wood pulp fibers [2]. Pressure screen systems, which fractionate fibers based on fiber length, are generally perceived as the most successful technology on a commercial stand-point [3]. In these systems, pulp slurries circulate between a stationary cylinder-shape screen and an external rotor. Pressure conditions between the screen and the rotor are such that the short fibers pass through the screen; long fibers are retained on the screen. The separation efficiency depends upon pulp furnish, use of perforated or slotted screens, pulp consistency, and input and output flow rates. The technology has high throughput. However, it has limited on-line adaptability to variable pulp furnishes and/or variable product requirements. These are drawbacks when one considers the ever increasing use of reclaimed fibers from mixed grades. Moreover, pressure screen

systems cannot fulfill fractionation requirements based on fiber radius, wall thickness, or coarseness, especially the separation of springwood and summerwood fibers.

The concept of acoustic separation is an interesting approach that may address some of the limitations of pressure screen systems. It is based on the use of a plane ultrasonic wave field to induce lateral deflections of moving fiber suspensions in a channel flow, and therefore, separate fibers accordingly to the deflection mechanism. Since the acoustic radiation force acting on the fibers is primarily a function of the fiber radius, large radius fibers are more deflected than small radius fibers. In practice, fibers interacting with the ultrasonic field can be collected by at least two discharge streams, one for the deflected fibers (large radius fibers) and one for the weakly deflected or undeflected fibers (small radius fibers and/or fiber debris).

Very little is available about the interaction of a sound field with fibers and more generally with prolate spheroids and cylindrical particles. Awatani was the first to calculate the acoustic force on a prolate spheroid [4] and a rigid circular cylinder [5], in plane traveling 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. More recently, Zhuk [6] and Wu et al. [7] reported independent derivations of the acoustic force on a rigid cylinder at stable orientation, in plane traveling and standing wave fields, respectively.

Dilute suspensions of flexible fibers (wood pulp fibers) subjected to a plane standing wave field have been investigated [8-11]. The development of acoustic separation and harvesting methods is an on-going research area [12-14]. One might say that these methods are

precision separation techniques when compared to the industrially driven separation concept

presented in this work. More specifically, they are suitable for microparticles and very small

flow rates; high throughput, power consumption, reliability, and hostile environment are not

relevant issues.

Theoretical Background

Separation methods using standing and traveling wave fields are considered here.

Focusing on the first case, the acoustic radiation force acting on a unit length circular cylinder

whose axis of symmetry is normal to a plane standing wave field is [7, 11]

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

(1)

where $f(\beta) = [[2(1-\beta) / (1+\beta)] + 1]$ is the inertia factor; $\beta = \rho_0/\rho_1$ is the ratio of the suspending

medium density to cylinder density; $k = 2\pi/\lambda$; λ is the acoustic wavelength; $\bar{E} = (p_0/c)^2/(2\rho_0)$ is

the mean energy density; p_0 is the static pressure; c is the sound velocity; h is the cylinder center

of mass position with respect to a nodal velocity plane. Eq. (1) indicates that F_{sw} is maximum

halfway between particle velocity nodes and anti-nodes and inversely proportional to the acoustic

wavelength. It specifies that the larger the cylinder radius, the larger the acoustic force.

Providing that β 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, fiber agglomeration is toward the nearest particle velocity anti-node at stable

acoustic equilibrium. The migration velocity under creep flow conditions was derived elsewhere

[11]. An equation similar to Eq. (1) for the acoustic force acting on a cylinder in a traveling

wave field is available from ref. 6.

Experimental Methodology

A schematic of the experimental setup to study fiber suspensions interacting with an ultrasonic wave field in a channel flow is depicted in Figure 1. The setup can accommodate zero-flow and laminar flow conditions. The maximum allowed fiber consistency is 1%. The suspending fluid (tap or degassed water) is first introduced in the flow system. This procedure provides a means to control the amount of dissolved gas in water when a standing wave field is prescribed. Next, fibers are injected and gradually mixed with the suspending fluid. The initial consistency can be increased by simply adding more fibers. A constant temperature circulator is used to control the temperature. On the right side of Figure 2, one distinguishes an in-line acoustic cell; it is mounted vertically to decouple gravitational and ultrasonic fields. The flow direction is reversible.

Acoustic Cell

The acoustic cell was designed to provide a maximum of flexibility. It is illustrated in Figure 2 for the case of a one-dimensional, unbalanced acoustic resonator. It consists of four identical and removable modular wall sections. The latter are individually used to support either a transducer, a reflector plate, an absorber plate, or a viewing port. The nominal length and width of these components are 100 mm and 20 mm, respectively.

The narrow-band, single-element transducer was designed to resonate at 150 kHz. Its rectangular cross-section insures that every fiber penetrating the ultrasonic field is submitted to the same acoustic dwell length. It is made of a graphite quarter-wave impedance matching layer

and several layers of a 2-2 composite piezoelectric material. Slicing was used to optimize thickness mode vibrations and field uniformity. Considering an approximate sound velocity in water of 1500 m/s at room temperature, the acoustic wavelength is 10 mm. Since the resonator length (transducer-reflector distance) is 20 mm, $\lambda/2$ is 5 mm, and four agglomeration planes are expected when a standing wave field is produced. The quarter wavelength is 2.5 mm; it corresponds to the typical average fiber length for softwood fibers (less for hardwood fibers).

A computer-controlled function generator and a broadband power amplifier were used to drive the transducer. The electrical power was limited to approximately 50 W RMS in most experiments. A rod-mounted, calibrated, 5 mm diameter, sub-MHz P(VDF-TrFE) hydrophone was used to evaluate field uniformity, pressure, and power. At 50 W RMS, the RMS static pressure measured at particle velocity nodes was about 200 kPa. The wavelength was stabilized against temperature variations by using a computer-controlled temperature compensation system. Finally, A CCD camera was used to record fiber trajectories in the acoustic cell.

Preliminary Results

Qualitative experimental results were gathered using rayon fibers and reclaimed wood pulp fibers. In the first set of experiments, rayon fibers suspended in degassed water were used to investigate acoustic agglomeration in a standing wave field under zero-flow condition. Affects of fiber radius and consistency were examined. Selected results are reported in Figures 3, 4, and 5. The transducer's and reflector's positions are on the left and right sides, respectively. Black areas refer to fibers because of back illumination. Fiber dimensions and consistency are as

follows: Figure 3 (length: 3.2 mm; radius: 5.9 μm; 0.1% consistency); Figure 4 (length: 3.2 mm; radius: 5.9 μm; 1% consistency); Figure 5 (length: 3.2 mm; radius 10.2 μm; 1% consistency).

As expected from design considerations, four agglomeration planes or layers are observed. At constant fiber radius, the layer thickness increases when the consistency increases (Figures 3 and 4). When the layer thicknesses for the 5.9 μm and 10.2 μm radius fibers at 1% consistency are compared (Figures 4 and 5), one observes thinner layers for larger radius fibers. This is a consequence of the acoustic force depending upon the square of the radius (see Eq. 1). As expected by the theory, the migration velocity is also increased [11]. There is no indication that the 1% consistency is an upper limit. In fact, a 2-3% consistency appears possible.

In the second set of experiments, the trajectory of rayon fibers suspended in degassed water was observed at 10 ml/s (Figure 6) and 50 ml/s flow rates (approximate figures). Flow velocities in the resonant cavity were 2.5 cm/s (R Å 500) and 12.5 cm/s (R Å 2500), respectively. The consistency was 1%. While the layers were well formed at R Å 500 (laminar flow regime), they were barely seen when the flow rate was increased by a factor of five. Since the acoustic power and/or the acoustic dwell length could not be increased to enhance fiber deflection, it was not possible to determine if the acoustic force was hindered by an excessive level of turbulence. Turbulent flow experiments were not performed.

In a different experiment, flowing reclaimed wood pulp fibers (more precisely, OCC or Old Corrugator Container fibers) were observed in a traveling wave field configuration. This is shown in Figure 7. The flow rate is 40 ml/s (flow velocity: 10 cm/s; R Å 2000). The consistency is 0.5 %. One can see that the fibers are pushed away from the transducer as they penetrate the

field; they tend to follow a parabolic trajectory. Additional observations obtained using fiber debris under similar flow/acoustic conditions have shown that the debris are barely affected by the acoustic field. Hence, the separation of fibers and fiber debris appears feasible.

Acoustic Separation Schemes

Qualitative results presented in Figures 3 to 6 support the standing wave field separation scheme illustrated in Figure 8. Large radius fibers are deflected toward anti-nodal particle velocity planes and collected appropriately. Fiber deflection (and separation) can be controlled by varying the acoustic dwell length (e.g., multi-element transducer), the acoustic power, and/or the frequency (assuming a broadband transducer). Dimensions are somewhat speculative: while the resonator length would be relatively small (few centimeters), its width would need to be sufficiently large to accommodate an acceptable throughput. Practical consistency would be 2-3%. Pressurization might be needed to eliminate the need for degassed water. A pressurized system might provide additional control by allowing the control of the discharge flow rates just like in pressure-screen systems.

A separation scheme similar to the previous one can be envisioned for a traveling wave field configuration. The concept is illustrated in Figure 9. On a practical stand-point, the traveling wave field configuration would be simpler to implement. Complete fiber deflection would imply fines removal (or thickening). The number of discharge streams could be more than two to classify fibers. One might think of using a receiving transducer as an active sound absorber to collect the residual acoustic energy (unused energy in the separation process), and therefore, recycle this energy back into electrical energy.

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Ultrasonic and Flow-field Fractionation of Suspensions," Ultrasonics vol. 32(2) pp. 113-

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Pierre Brodeur
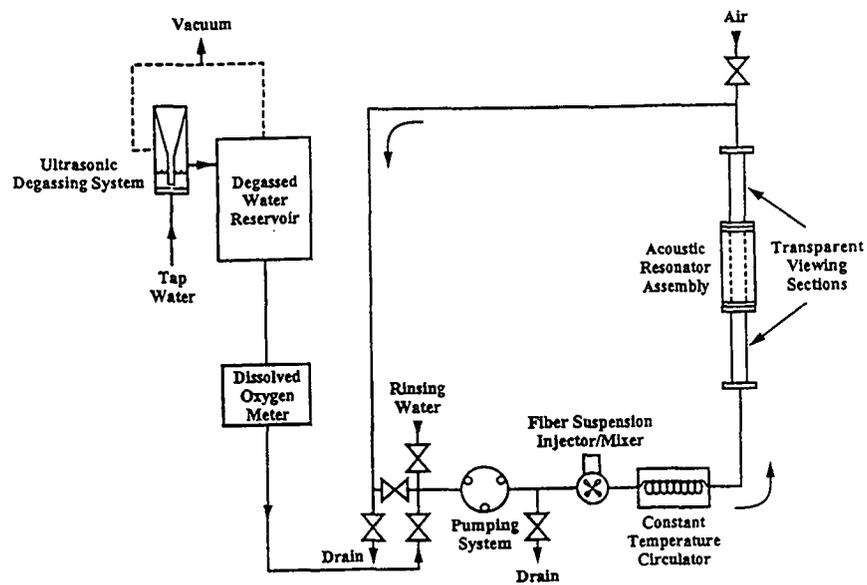Assistant Professor of Physics
Engineering and Paper Materials Division

Figure 1.   Schematic of the experimental setup to study acoustic radiation effects on moving
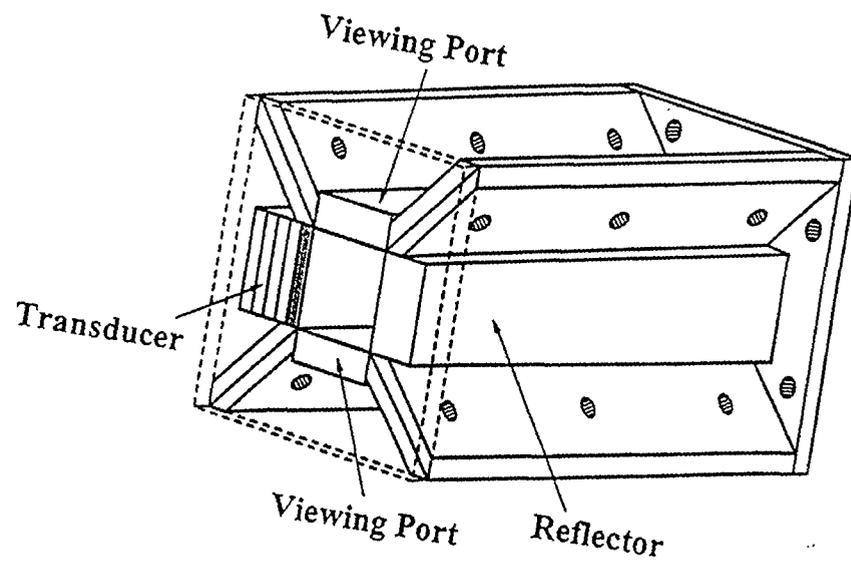
fiber suspensions.

Viewing Port

Transducer

Viewing Port   Reflector

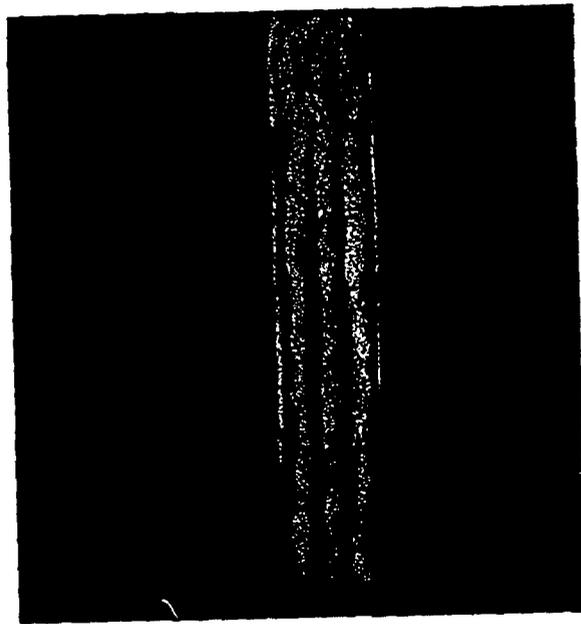Figure 2.   Schematic of the acoustic cell for the case of a one-dimensional, unbalanced acoustic resonator.

Figure 3.   Agglomeration of 5.9 μm rayon fibers at 0.1% consistency (no flow).

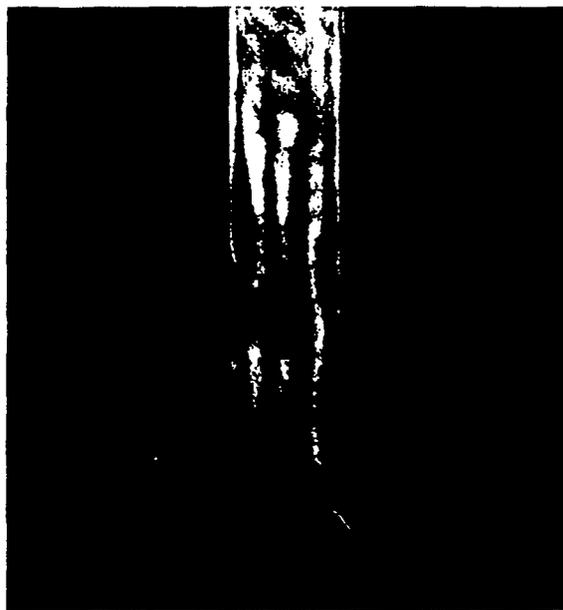Figure 4. Agglomeration of 5.9 μm rayon fibers at 1% consistency (no flow).

Figure 5.   Agglomeration of 10.2 µm rayon fibers at 1% consistency (no flow).

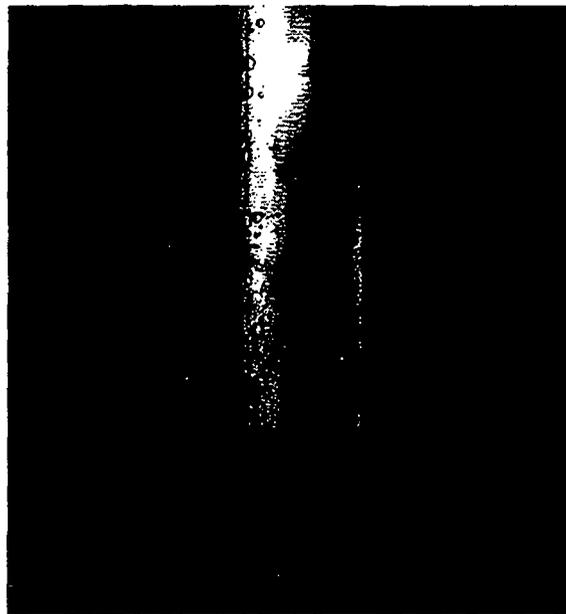Figure 6. Trajectory of 5.9 μm rayon fibers at 1% consistency and 2.5 cm /s flow velocity.

Figure 7. Trajectory of reclaimed wood pulp fibers interacting with a traveling wave field. The flow velocity is 10 cm/s.
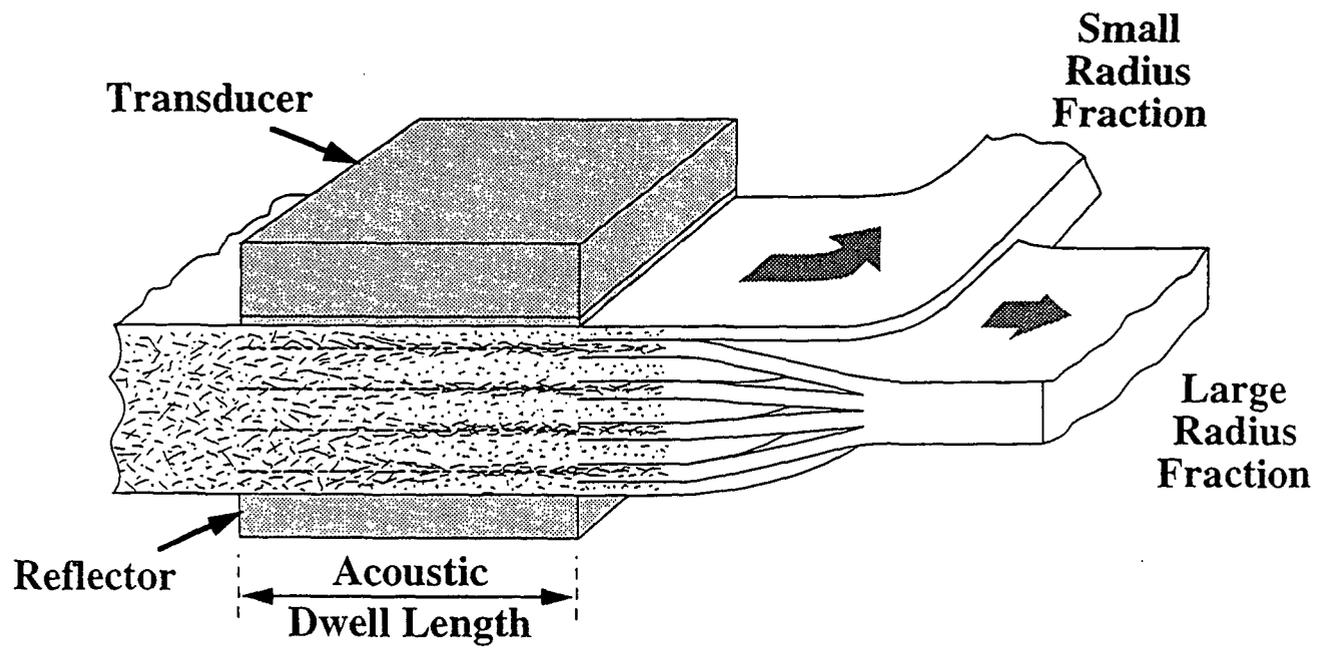
Figure 8.   Proposed acoustic fiber separation concept using a standing wave field.

Transducer

Small
Radius
Fraction

Absorber

Acoustic
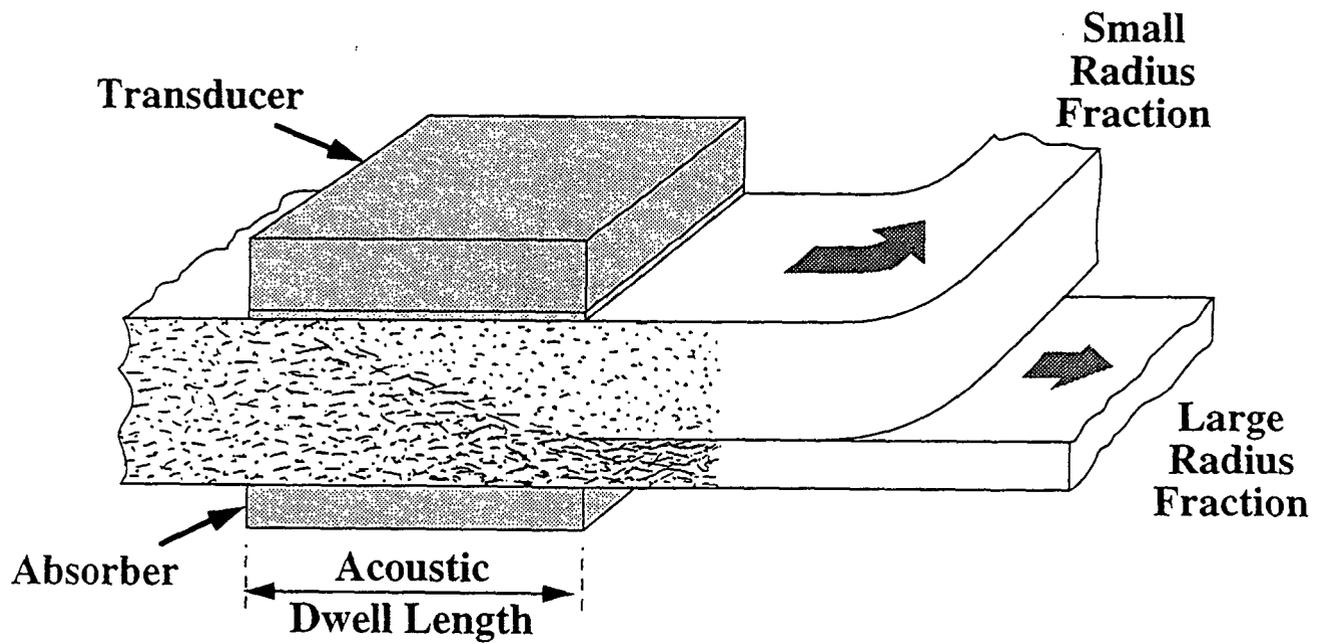Dwell Length

Large
Radius
Fraction

Figure 9.   Proposed acoustic fiber separation concept using a traveling wave field.