Melde’s experiment consists of a taut string with a periodic driving force applied to it.\textsuperscript{1-3} With the proper conditions for resonance, the string will vibrate with great amplitude. A typical standing-wave pattern has large-amplitude vibration throughout the string between points of no motion called nodes, which surprise students so much that they often must touch them to believe they are there! Standing waves are usually explained as interference between transmitted and reflected waves,\textsuperscript{4} but especially for those uncomfortable with the oxymoron “standing wave,” the pattern can also be explained as the eigenmodes of oscillation of a continuous system.\textsuperscript{5} The distance between adjacent nodes in the string has a length corresponding to one-half wavelength of the wave traveling through the string.

Sometimes Melde’s experiment is done with signal generators passing current through a wire in a magnetic field, allowing the student to tune to resonance by tuning the frequency (our former method).\textsuperscript{6} At constant frequency, it is also possible to tune to resonance by adjusting the speed of the transverse wave, accomplished by adjusting the tension on a string. Less expensive commercial vibrators are available that oscillate a metal plate under an electromagnet driven by line current.\textsuperscript{7}

Noncommercial vibrators have been made from loudspeakers,\textsuperscript{8} doorbell-clappers,\textsuperscript{9} buzzers,\textsuperscript{10} motors,\textsuperscript{11} hair cutters,\textsuperscript{3} jigsaws,\textsuperscript{3} and ac-dc converters,\textsuperscript{12} but the method I describe here came from a childhood memory of when my older brother Bob showed me the inside of an aquarium aerator. An aerator consists of an electromagnet driven by line current that shakes a magnet glued to the end of an armature. This in turn drives the bellows that pump the air. The frequency of the vibration is the line frequency of the current, which

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**Melde’s Experiment with an Aquarium Aerator**

**Rich Dynamics with Inexpensive Apparatus**

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is 60 Hz in the United States, and is the source of the obnoxious drone you hear in a pet store. [Note: Commercial vibrators produce a frequency of twice the line frequency because the electromagnet drives a steel plate (no permanent magnet) that is attracted to the electromagnet twice each cycle.]

**Apparatus Setup**

To use the aerator to drive a string, unscrew the bottom of the pump (unplugged of course) and tie a string to the end of the armature (see Fig. 1). It is prudent to wrap tape around the transformer end to prevent maverick fingers from touching electrical connections. You can immediately show standing waves by just holding the pump in one hand and tugging on the string with the other. For a more controlled demonstration, secure the aerator to the table with a C clamp and run the string over a pulley. Hang a cup containing gunshot, sand, or even water on the end and adjust the weight to create the standing wave. The speed of the waves, $c$, is found by weighing the cup for the tension $T$.

![Fig. 2.](image1.png) **Fig. 2.** Left: standing wave in homogeneous string for which each swell has the same length, even though they appear smaller in the distance. Right: tapered fly line grows thicker with distance. Swells in foreground are longer than neighbor to left, but swells in distance become smaller, implying that wave is slower in thicker end of fly line.

weighing a long piece of string of known length for the linear density $\mu$, and computing $c = \sqrt{T/\mu}$. The standard formula $\lambda = 2L/n$, which includes the assumption that the length of the string corresponds to an integral number of “swells,” should not be used because the vibrator position is neither a node nor an antinode. If you look closely at one of the standing waves made by this device, the swell nearest the vibrator is shorter than the others. The wavelength is measured as twice the distance between two nodes. Many modes may be obtained, and we have gotten as few as two antinodes for a length of string greater than a meter. Upon graphing wavelength versus speed, students measured a line frequency with no more than 5% error.

A few techniques will maximize the amplitude of the standing waves. First, the tension can be carefully tuned by using a spoon to deliver sand slowly into the bucket when the system is near resonance. Second, the great tension required to achieve small numbers of antinodes will eventually tug the vibrating arm so far away from the electromagnet that it is no longer driven. You can prevent this by clamping the aerator at an angle so the arm is as much parallel to the direction of the string tension as possible. Finally (as teachers at our 1997 summer workshop discovered), if the pump is prevented from pumping air, the standing wave amplitude will be greatly enhanced. You can glue the aerator’s spout closed or insert one of the backing screws into the spout. When all of these techniques were applied, we got antinode widths sometimes of an inch and a half!

**Phenomena with Standing Waves in a String**

The criterion for the formation of a standing wave is that after transmission, the reflected wave returns to

![Fig. 3.](image2.png) **Fig. 3.** Standing waves in a string appear colored when viewed in fluorescent light, which emits different intensities of color throughout cycle. Viewed from above, standing wave appears blue on the edges; viewed sideways, edges appear orange.

![Fig. 4.](image3.png) **Fig. 4.** Mode created when typical twirling string sways at half the vibrator frequency. Close-ups of string’s cross section in lower left shows two typical Lissajous trajectories of an element of string, photographed by sweeping a laser through the standing wave.
Students are mesmerized when the device is shown with a strobe light at the line frequency. (But, stroboscopic light can induce epileptic seizures, so epileptics should be warned not to watch.) Observers can distinctly see the pump arm “slowly” oscillating back and forth. The strobe light reveals that the string vibration is usually circular motion (see cover photo), just as when children play jump rope, and the rope appears as a rigid structure just rotating, not oscillating. Rotation is natural for a system being driven only along one direction. The twirling string may be thought of as two transverse waves in orthogonal planes a quarter cycle apart, just as two modes of polarization describe circularly polarized light.

The twirling string may be literally viewed this way if it is lit by fluorescent lighting. You may notice reddish and bluish tints to the standing wave (see Fig. 3), especially if the string is white and viewed against a black background. Fluorescent lights do not emit all colors simultaneously with equal intensity along the phase of their line cycle, which is the same frequency as the vibration of the string. When viewed from above, the wave appears one way, perhaps red in the middle and blue on the edges, but when viewed sideways, the colors are swapped because of the quarter-cycle difference in phase. When you tune past maximum resonance of the standing waves, the color scheme will switch because of the change in phase of the string’s vibration with respect to the driving force. The direction of the rotation also switches, as a stroboscope reveals.

The picture on the cover was taken by first photographing the vibrating string under stroboscopic light at five times its vibrational frequency. A side-by-side pair of red and green laser beams were then sliced perpendicular directly through the vibrating string. The resulting picture reveals that when this is repeated at intervals along the length of the string, the motion of a string particle is indeed circular.

A more sophisticated trajectory occurs (see Fig. 4) when an additional mode at half-line frequency develops in one plane while the string is being tuned to an even number of swells. Half-frequency vibrations occur when a string is being driven longitudinally rather than transversely. If you were holding a planar standing wave in a rope, from its stretching you would feel the tension increase above default twice each period. You might try to excite the wave by just varying the tension, one example of parametric excitation. However, by driving your hand longitudinally back and forth at the same frequency of the existing standing wave, you would only increase the tension above default once each period, producing a standing wave at half frequency. The tendency for the string to jump into this mixed subharmonic mode can be annoying when you’re taking data for Melde’s experiment itself, but can be quelled by pinching the string at one of the splaying would-be nodes of the expected pattern.

The ability to pinch a node while leaving the pattern beyond unaffected makes transverse waves difficult to believe in. Although planar waves in a string are presented as the archetype of transverse waves and are even modeled this way in advanced mechanics books, the motion of an element of string in a planar vibration cannot in general be just strictly transverse. To vibrate, the string must stretch, and the stretching of an element of string is a maximum where the slope is greatest. “Transverse” waves might better be referred to as planar waves, because the stretching of an element of string means a point on the string undergoes both transverse and longitudinal motion. This means energy can be transmitted longitudinally through the node.

The stretching of the string makes the equations of motion nonlinear. This effect results in exceedingly rich dynamics when driven sufficiently hard. When the tension is slowly changed, you can observe such diverse behavior as beats, slow swaying and rotation of vibrational planes, switching from planar to rotational motion, and jumps in amplitude.

In about an hour and with a total cost of about ten dollars per apparatus, teachers at our Advanced Placement Physics Teachers Workshop constructed a standing-wave generator from an aquarium aerator, took the data, and deduced the vibration frequency. I hope that other teachers will find this an exciting and easy laboratory as well.

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