WAVES
STEADY OR PULSED, STANDING OR TRAVELLING

Objectives

- to understand the nature of wave propagation
- to visualize the relationship between standing and travelling waves
- to understand resonance when a sinusoidal wave travels in a (linear) cavity

References

- The waves chapters in your first year physics text - for example:
- R Wolfson & J M Pasachoff, *Physics with Modern Physics*, (Addison Wesley 1999); Chap 16, 17
- R A Serway, *Physics for Scientists & Engineers, Vol 1*, (Saunders 1996); Chapters 16, 18
- A P French, *Vibrations & Waves*, (Norton 1971); Chapters 7, 8

Introduction

We all experience waves, the phenomenon whereby the medium in which the wave occurs is not transported, but the motions of that medium travel onwards. From a young age we watch water ripple in our baths, wind blowing grasses in fields, water patterns following boats we are in, stop lights travelling up a row of cars when the first one applies its brakes. As we became scientifically more sophisticated we recognized that these phenomena have a commonality with sound propagation, light propagation, and the vibration of a guitar or violin string. This experiment is designed to help you develop a gut feeling for the way waves move and what happens when waves are reflected.

Waves take place when a succession of physical units are coupled together in such a way that a disturbance of some physical property in one unit affects the neighbouring unit, but with a delay before the effect is seen. The physical property and the mechanism providing the coupling varies from one type of wave to another.

Waves in the Shive Wave Machine are non-dispersive. This means that their speed of propagation is constant, independent of frequency. Thus $f = c/\lambda$, where c, the speed, is a constant, f is the frequency and λ is the wavelength. (Waves on stretched strings are non-dispersive waves.) It should be pointed out that most waves found in nature are dispersive (their speed of travel depends on their frequency), and that this apparatus is not capable of demonstrating phenomena associated with this property.

The Apparatus

In this experiment we use a wave machine devised by Dr. John N. Shive at Bell Labs in the early 1960s to illustrate various types of waves. The physical property is the angle of tilt (θ) of metal rods. The coupling is provided by the torque (τ) produced in a steel wire between adjacent rods when the angle of one rod is different from its adjacent rod. The time delay is provided because the torque is proportional to an angle while the rotational mass (moment of inertia) provides a response involving a time-second-derivative of the angle. $\left[I \frac{d^2\theta}{dt^2} = \tau_{net} , \quad \tau = k(\theta_2 - \theta_1) \right]$ This arrangement permits a highly-visible, slow-moving (about 50 cm/s), mechanical wave.

As a wave moves along the machine, there is little energy loss, as the torsion wire is of good quality steel which is highly elastic. The main energy loss comes from the air resistance (air viscosity) as the rods move. This has the benefit that a wave started down the machine, to then be reflected, will continue for a long enough time to permit the observation of the effects of the multiple reflections that produce standing waves. The down side of this is that a wave disturbance, once started, keeps the apparatus moving for up to a minute. Thus, you will find that if you change conditions of motion of the apparatus, the pure effect you are looking for will not be completely present until about a minute has passed.

Another limitation of the apparatus comes from the length of the rods which are susceptible to air currents in the room. This means that small responses and motions of the wave machine will not be observable because of the "noise" implied by the random air currents.

The drive:
For pulsed signals, you can drive one end of the wave machine by shaking the end rod up and down by hand. For pure single-frequency sine wave motion, you can drive that same end with the loud speaker that is coupled to the end rod by feeding the appropriate electrical signal from a signal generator. When you use the Wavetek signal generator, you can vary its frequency using the frequency knob and buttons. The size of the signal is controlled by the amplitude knob which you will probably want to keep at its maximum setting.

The termination:
You can terminate the other end of the wave machine in one of three ways. **(i)** A dash-pot, filled with water and attached to a point half-way out the last rod, provides energy dissipation so that a wave arriving at that rod does not get reflected as almost all its energy is absorbed due to the viscosity of the water. **(ii)** A clip on a stand permits the last rod to be clamped, held stationary, so that no energy can be lost at the end, providing a condition for complete reflection of a wave arriving at that rod. **(iii)** The last rod can be left free, so that no energy can be lost at the end as no force is applied to the end, providing a different condition for complete reflection of a wave arriving at that rod.

The loud speaker as a microphone:

Instead of using the loud speaker to drive the machine, you can connect it to an oscilloscope. The loud speaker then acts as a microphone and the velocity of its motions produces a voltage which will be displayed on the oscilloscope as a function of time.

What to Do

1. <u>Qualitative Pulse Behaviour</u>:
(a) With the dash-pot (**i**) at the termination end, by hand give the rod at the loud speaker end a single quick up-down shake. Observe the wave that results and estimate its speed. Which way are the rods moving? Which way is the wave moving? Is the wave's energy being absorbed by the dash-pot?

(b) Repeat the above with the termination end clamped (**ii**), and **(c)** repeat the above with the termination end free (**iii**). Note the reflection in both cases. Comment on the size of the reflected wave. Can you observe the phase of the reflections relative to the arriving wave?

2. <u>Speed of the Wave</u>:
With the loud speaker connected to the oscilloscope CH1 input and with the (**ii**) clamped termination and then with the (**iii**) free termination, hand-shake the rod at the speaker end. Notice the traces on the oscilloscope indicating the motion of the end rod. Suggested settings for the oscilloscope are:

> *CH1 menu:* Coupling=DC, BW Limit=ON(20MHz), VOLTS/DIV=100mV
> *TRIGGER menu:* Source=CH1, Mode=Normal, Coupling=DC, TRIGGER LEVEL=about 30mV
> *HORIZONTAL:* SEC/DIV=1s

Measure the time between successive pulse wave arrivals to the speaker and calculate the speed of the wave. Can you see any difference in the phase of the reflected pulses between the clamped and the free cases?

3. <u>Sinusoidal Travelling Waves</u>:
With the loud speaker connected to the signal generator and the signal generator set for sine wave output, and with the **(i)** dash-pot termination, slowly scan a range of frequencies from 0.3 Hz to 4.0 Hz and watch the wave behaviour. For frequencies 0.3Hz→0.4Hz→0.5Hz, note the phase difference of the motion along the machine. For frequencies 0.5Hz→1.0Hz→1.5Hz→2.0Hz→3.0Hz→4.0Hz watch the actual motion of the wave along the machine. (What do you perceive is moving?) *Estimate* the wavelength for some of the frequencies. Does your estimated wavelength and the frequency match the speed you calculated in part 2?

4. <u>From Travelling Waves to Standing Waves</u>:
With the setup of part 3 (the speaker driven by the signal generator at one end and with the dash-pot at the other end) and a frequency of 0.85 Hz, observe the travelling wave. Then clamp the rod at the dash-pot end and observe the evolution to a standing wave.

5. <u>Standing Waves - Clamped End</u>:
With the setup of part 4 (the speaker driven by the signal generator at one end and the clamped rod **(ii)** at the other end) scan frequencies from 0.6 Hz to 2.2 Hz.

Notice that, because of the reflected wave from the clamped end, standing waves exist for all frequencies, with distance between nodes being one half the wavelength. The imposed clamp at the termination end makes that end a node. However a resonance phenomenon exists whereby there is a maximum amplitude of the wave at frequencies corresponding the loud speaker end being approximately a node. (At frequencies sufficiently away from resonance, the standing wave is hard to see because the amplitude of the wave becomes smaller than the noise from air currents.) Notice what happens to the position of the node nearest the loud speaker as you change the frequency from below resonance to above resonance.

Find the resonant frequencies for the number (n) of anti-nodes in the standing wave pattern ranging from n=2 to n=8. Plot a graph of resonant frequency as a function of n, and compare its slope to the reciprocal of the time between successive pulses that you found in part 2.

The wave machine with reflecting ends parallels the situation of an electromagnetic wave or a sound wave moving in a cavity. This machine is now a one-dimensional cavity.

6. <u>Standing Waves - Free End</u>:
Now, with the setup of part 5 with the termination end rod free **(iii)** scan frequencies from 0.45 Hz to 2.1 Hz. Again find the resonant frequencies and plot these on the same graph as in part 5. Are the two plots part of the same curve? Notice the motion of the free termination end under this condition.

Put the clamp at a rod corresponding to a node. How is the standing wave pattern altered?

Comment

At each stage of this experiment, make sure you understand what is happening and why the wave motions behave the way they do and the reasons for the various phenomena you observe. If you can't figure it out, consult one of the references, then consult another student, then consult a demonstrator. All these resources are here to help you conceptualize wave phenomena.

jbv - 2000