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***Abstract*—As an echolocating sensor moves through an environment the pattern of echoes reflected by objects to that sensor changes continuously, creating acoustic flow. Acoustic flow has been observed in both bats and humans. In this paper, we develop a theory of acoustic flow, and discuss measuring it with a Continuous Transmission Frequency Modulated (CTFM) ultrasonic sensor.**

I. Introduction

Acoustic flow is a term coined by biologists to describe some of the abilities of echolocating bats [2, 16]. Some studies have shown that bats behave in a way that is consistent with the concept of acoustic flow [14]. As an echolocating sensor moves through an environment the pattern of echoes reflected by objects to that sensor changes continuously, creating acoustic flow. Acoustic flow contains information about the geometric relationship between objects, the surface geometry of those objects and the motion of the objects relative to the sensor.

Acoustic flow can be understood as follows. Imagine that you are sitting in a room with your eyes closed. Objects in the room emit audio tones with frequency proportional to their range from you. Objects with simple shapes emit simple tones and objects with complex geometry emit a spectrum of tones. The amplitude of these tones is proportional to the surface area of the object facing you. The direction from which a tone comes is the direction to the emitting object. These sounds can be described as an acoustic field. From this field you can perceive the location of objects.

Imagine that the objects start to move. As a result of their motion, the tones that you hear change in frequency, amplitude, direction and spectral content. The frequency change is due to change in range. The direction change is due to change in direction. The amplitude change is due to object rotation changing the audible surface area. The change in spectral content is due to a combination of the above. This dynamically changing acoustic information can be considered to be an acoustic flow field. From this field you can perceive the motion of objects.

Imagine that you are moving through this environment. As you move toward an object, its frequency decreases in proportion to the relative velocity between you and it. As you pass the object, its frequency drops until you are beside it and then increases as you move away from it. Your ears sense this decrease in frequency followed by an increase in frequency as a flow pattern. This flow pattern is accentuated by the fact that the rate of change of the frequency also decreases and increases. In contrast, when you are moving directly toward an object, at fixed velocity, the frequency decreases but the rate of change of frequency doesn't while the amplitude increases giving you the sense that the object is looming toward you.

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Leslie Kay has been developing mobility aids for blind people for thirty years using Continuous Transmission Frequency Modulated (CTFM) ultrasonics [11, 12]. The ultrasonic sensors used in the Kaspa mobility aid produce stereo tones that are proportional to range. From these tones blind people can gauge the distance and direction of objects. With training they show considerable ability both in navigation and in recognising objects with this sensor.

Many of these people report that they can hear objects move by perception of acoustic flow [6]. They also report that it is easier to discriminate moving objects than stationary objects in a complex environment. They continuously move the sensor to hear information produced by the relative motion of the sensor to the environment. One teacher has taught a blind boy to hit a softball pitched toward him with a baseball bat [1].

It appears that the relative motion between the sensor and the object significantly increases the information content of the echo. Motion will change the echo in several ways. Linear velocity toward or away from the sensor will result in proportional frequency and amplitude changes. Angular velocity around a sensor will result in changes in amplitude and frequency response with angle due to the transducer's beam pattern.

Acoustic flow may give us another option when developing a mobile robot navigation system [5]. While this paper is limited to studying the theory, in future research we will look at how measurement of acoustic flow can be used to track targets, to build dynamic maps and to achieve behaviour based control. A number of researchers have looked at aspects acoustic flow.

Reece [17] developed a model to calculate the curvature of surfaces using odometry measurement of robot velocity together with ultrasonic range data. Although, he called this model acoustic flow, it is significantly different to the model proposed here. Carmena [3] and Muller [16] developed models of the acoustic flow due to Doppler shift of constant frequency (CF) signals. Jenison [10] developed a model of acoustic flow in 2D space from a kinematic model of the motion of a sound source.

In drive-by-scanning [13], retro-reflectors, such as corners, produce strong echoes from a range of sensing angles. By detecting a corner multiple times as it drives past a robot can measure its trajectory. Direct measurement of the acoustic flow of the corner reflector may provide trajectory information in a more timely manner.

We have set out to develop a theory of acoustic flow both to understand it and to provide a theoretical basis for applying it to sensing situations, in particular the control of mobile robots. To derive this theory we have listened to the sensor outputs, thought about the physics of the sensing system, examined the equations of the optic flow analogue, and conducted experiments. This paper presents initial results of that research.

II. Animal and Human Physiololgy

As an echolocating bat flies through an environment, it emits chirps at ultrasonic frequencies, which reflect off objects to produce a sound field that is continuously changing [9]. The motion of this sound field into the bat's ears can be described as a flow of acoustic information. When the bat lands on an object it follows a trajectory that results in zero velocity at the time of contact. Recent analysis of these trajectories has shown that bats use a principle of acoustic flow similar to the principle of optic flow used by birds and humans [8, 19]. The parameters of this acoustic flow field are determined by the location, motion and reflection properties of the insonified objects.

Physiologists have noticed that humans have a perception of sound that could be compared to acoustic flow. Reiser et. al. [18] put forward the idea that if blind people were trained in a controlled acoustic environment they would perceive acoustic flow patterns which had properties analogous to optic flow.

Some have trained blind and sighted people to measure differences between them in spatial perception using only sound. Two methods where used. The first method used controlled sound sources where objects actually emit sounds that the blind person navigates by. The second method used a CTFM mobility aid developed by Leslie Kay [12]. He hypothesised that both methods require a concept of acoustic flow for estimation of spatial information.

Shaw et al [19] introduced the concept of a Tau variable to human perception. The Tau variable was originally developed as a time to contact variable based on optic flow calculations by Lee [14].

Work on time to contact and tau calculations has continued in research into human perception. Hellman [9] conducted a study on the time-of-arrival of moving sound sources. He confirms that "human listeners are able to perceive the approach of sound sources and to judge their time of arrival based on auditory information." He also says these perceptions are "very similar to those found in visual studies." This adds weight to the idea of acoustic flow.

At the University of California Riverside research was done into human perception of acoustic flow [20]. They constructed a "large moveable 'acoustic room'" which they can move to simulate movement of the listener. They have discovered "evidence for perceived self-movement thereby replicating analogous results in optical flow research".

III. CTFM Sensor

An acoustic flow field can be produced by a CTFM ultrasonic sensor. CTFM produces a set of continuous tones where the frequency of each tone is proportional to the range to a reflecting object [15]. For example, a plant produces a complex tonal structure (Fig. 1.) Multiple receivers enable the calculation of object bearing. When an object moves the tones change in frequency and amplitude, and the time relationships between the signals at the receivers change to produce an acoustic flow field. You can listen to the audio signals and hear the acoustic flow field in the room in which you are moving.

A CTFM system transmits a sine wave that is repeatedly frequency swept over a one-octave bandwidth (f_{sweep} is 100 to 50 kHz with a sweep period t_s of 102.4 ms). The echo is a delayed and filtered version of the transmitted signal.

The echo is demodulated with the transmitted signal to obtain a set of audio tones (f_a is 0..5KHz) proportional to range (Fig. 2.). The audio tone for a target is continuous from the time at which the echo arrives until the end of the sweep. Thus, the sweep consists of two time periods: the time to the arrival of an echo from maximum range (t_d) and the time to capture the samples (t_0) for the Fast Fourier Transform (FFT)

In the time domain, the complexity of the audio signal is proportional to the geometric complexity of the target. It contains a tone for each range where sound is scattered. We can separate these tones by transforming the audio signal into the frequency domain by calculating its power spectrum using an FFT.

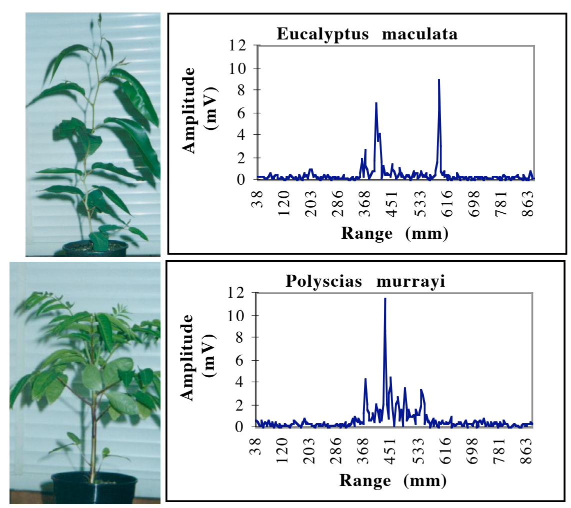

Fig. 1. Echo spectra of plants (a) Eucalyptus maculata and (b) Polyscias murrayi. Range on X axis = frequency multiplied by mm/bin.

The FFT divides the echo up into $n = 512$ frequency bins of width $\delta_f = 10$Hz (Fig. 3.). When transformed from frequency space to geometric space the bins represent a set of concentric annuli each $\delta_r \approx 3.4$ mm thick (Varies with temperature and with different sensors). The frequency of an FFT line f_m is proportional to the range r_m to the annulus containing the surfaces that produced that component of the

echo. Thus we have a range-energy envelope where the amplitude of a bin is the energy per unit time reflected from the surfaces in its annuli.

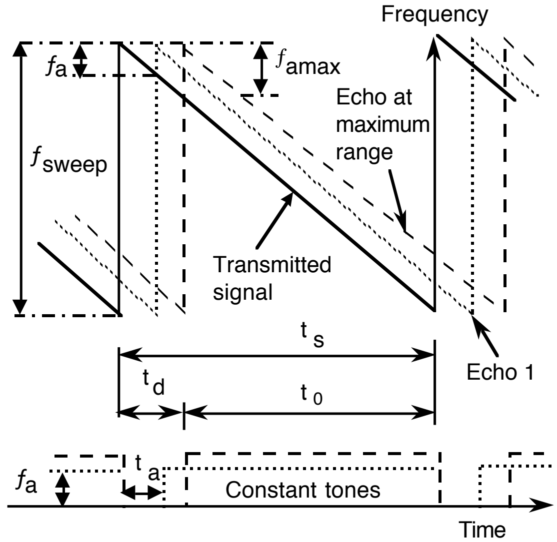

Fig. 2. CTFM systems demodulate the echo with the transmitted signal to produce an envelope of constant frequency tones. f_{sweep} = sweep frequency range, f_a = audio frequency, t_s = sweep time, t_d = time to echo at maximum range, t_o = time period for FFT sampling, t_a = time to echo

The amplitude A_r of the FFT line at range r (Fig. 3.) is the absolute value of the complex number output from the FFT. It is the energy of the echo in milliwatts and is proportional to the pressure of the echo and hence to the area of the surfaces in the annulus that are normal to the receiver [15].

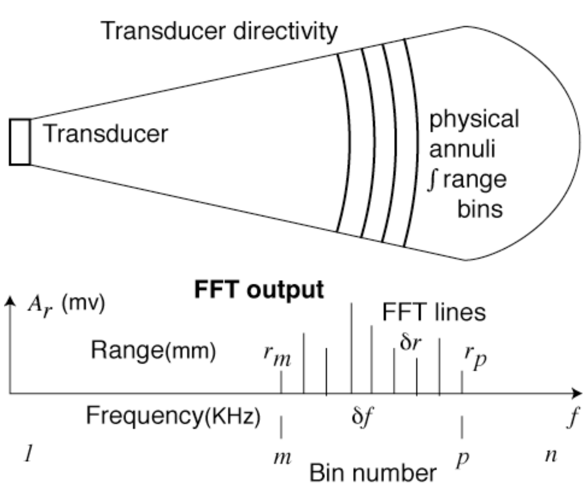

Fig. 3: The amplitude of each spectral lines produced by the FFT is proportional to the density of acoustic reflectors in the annulus at that range.

IV. Optic Flow Analogue

The first place an analogy was drawn between optic flow and acoustics was in bat echolocation. Lee *et al.* [14] put forward that idea that there might be similar perception and action ideas from both vision and hearing. They developed a theory of visual control of braking based on time-to-collision, which they extended to echolocation.

In this theory, a single variable called the tau variable is derived from flow information and allows for control of braking. The most attractive aspect of this method of braking control is its simplicity - it was no longer necessary for animals to detect distance to target, current velocity and then calculate necessary deceleration.

A generalised theory can be described as follows:

Let $P = P(t_1, x_1 .. x_n)$ (1)

be a sensory variable that represents a feature in the real world. It depends on time t_1 and a set of spatial variables $x_1..x_n$. The flow of that sensory variable is the apparent motion of pattern in the sensory variable described by a flow vector:

$$q(x_1 .. x_n) = \left\langle \frac{\partial P}{\partial x_1} .. \frac{\partial P}{\partial x_n} \right\rangle \quad (2)$$

In optic flow, the sensory variable is brightness across a 2D image. The spatial information restricts the real-world places that the sensory variable can correspond to. For optic flow, the spatial variables restrict the brightness feature in the world to lie on a straight line from the point on the image through the focal point of the camera. As a result, flow can be used to calculate the position and velocity of objects.

In CTFM ultrasonics, the sensory variables fit a 1D case of the above general theory [4]. A CTFM sensor produces a signal with frequencies that are proportional to range. The power spectrum of this signal is an envelope of frequency lines. As an object moves these lines move. The amplitude of the signal A is a function F_1 of time t. To extract the frequencies, we perform an FFT.

$$A = F_1(t) \quad (3)$$

When an object moves, its frequency changes due to the change in range. The relative velocity of an object with respect to the sensor is proportional to the frequency change. This change can be measured by comparing the outputs of the FFT across time. Thus, we have an acoustic variable as a function of frequency and time,

$$A = A(f, t) \quad (4)$$

and acoustic flow q as a function of δf between FFT outputs. The frequency change is proportional to the component of motion along the vector from the sensor to the reflecting object. Thus, it is a direct measure of the relative motion of the object along this vector.

V. Acoustic Flow Theory

We present a theory for the case of a single monaural sensor, like the K-Sonar, and a single object (Fig. 4.). There is insufficient space to extend it to multiple objects, multiple sensors, sensor arrays and Doppler shift. A sensor frame **S** is located at the face of the sensor with its x axis along the beam axis and its y and z axes in the plane of the face. An

object frame **O** is located on the object at location (r, b, e)(*range*, *bearing*, *elevation*) relative to the sensor frame. A single sensor can measure the range to objects that lie within the field of audition defined by the sensor's directivity function. For a monaural sensor the resolution of the bearing and elevation is twice the beam angle ($\pm\beta$).

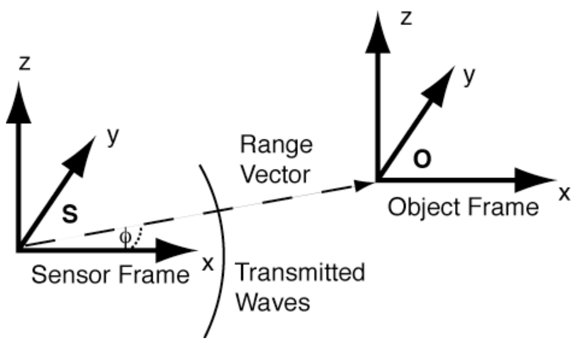

Fig. 4. Coordinate frame model for acoustic flow theory

In time δt an object moves a distance δd from (r_t, b_t, e_t) to (r_{t+1}, b_{t+1}, e_{t+1}) resulting in a change in range of:

$$\delta r = r_{t+1} - r_t. \tag{5}$$

This change in range causes a change in audio frequency δf in the demodulated echo, where $S\delta f = \delta r$, $Sf = r$ and S is a scale factor from frequency to range. The general equation for the change in range of a point (x, y, z) due to pure translation is

$$\delta r = \frac{x\delta x + y\delta y + z\delta z}{r} \tag{6}$$

δr is the component of motion along the range vector $\boldsymbol{r}_{so}$ from the sensor to the object. Thus, δf is a direct measure of the motion along this vector. The change in amplitude is:

$$\delta a = F_2(r, g) \tag{7}$$

where a is the amplitude of the echo and g is the surface geometry and F_2 is a function.

In many sensing situations, acoustic flow in one dimension may provide sufficient information for the task. When we consider the motion of the sensor and the objects within the physical constrains of ultrasonic sensing, we can decompose relative motion between these two 6 DOF frames into 8 components: 3 of translation and 5 of rotation:

1. Translation of δx along a vector parallel to **S**x results in

   $$\delta f = \delta r = \frac{x\delta x}{r} \tag{8}$$

   When the motion is in the xy plane of the sensor frame this equation reduces to

   $$\delta f = \delta r = \delta x * \cos(\phi) \tag{9}$$

   where ϕ is the angle between the direction of motion and the vector to the object.

   When $\phi = 0^o$, this motion results in collision, so r -> 0, and for a fixed velocity $\delta\phi$ is constant. When $\phi <> 0^o$, this motion results in the sensor passing the object, so $\delta\phi$ decreases until the sensor is beside the object and then increases.

2. Translation of δy along **S**y by the sensor or along **O**y by the object results in:

   $$\delta f = \delta r = \frac{y\delta y}{r} \tag{10}$$

   This motion results in both f and δf passing through minima when the origin of the object frame **O** passes through the xz plane of the sensor frame **S**. When x = z =0 the frequency f is also 0.

3. Similarly, the orthogonal case of translation of δz along **S**z results in:

   $$\delta r = \frac{z\delta z}{r} \tag{11}$$

   and both f and δf pass through minima when the origin of **O** passes through the xy plane of **S**.

4. Rotation of $\delta rotx$ around **S**x or **O**x results in

   $$\delta f = F_3(s) \text{ and} \tag{12}$$

   $$\delta a = F_4(r, s) \tag{13}$$

   where s is a measure of the symmetry of the surface around the x axis. Rotating the object around either x axis will cause a change in the spectral content of the echo only when the object is not symmetric with respect to the axis of rotation.

5. Rotation of $\delta roty$ around **O**y results in

   $$\delta f = F_5(g) \tag{14}$$

   As the relationship between the origins of the frames does not change, any changes in spectral content are due to surface variations in the object. When irregularly shaped objects rotate, the point of reflection may vary rapidly causing discontinuities in range and bearing measurement. In our classification research [15], we observed that features extracted from the demodulated echo vary less with rotation than the echo spectrum does. Variation with motion gives many objects a characteristic set of temporal features.

6. Rotation of $\delta rotz$ around **O**z results in the same δf and δa as case 5

7. Rotation of $\delta roty$ around **S**y results in

   $$\delta f = 0 \tag{15}$$

   The object moves in the annulus at range r from the sensor, and the point at which the vector from the sensor to the object $\boldsymbol{r}_{so}$ intersects the object doesn't change.

8. Rotation of $\delta rotz$ around **S**z results in the same δf and δa as case 7.

Doppler shift occurs in addition to the frequency change with motion. While the change due to Doppler shift is small compared to that due to motion, it is not time dependent and has the potential to provide more instantaneous perception.

VI. MEASURING ACOUSTIC FLOW

Before we can apply the above theory to develop sensing applications for mobile robots, we have to validate it. In order to validate it we have to learn how to measure acoustic flow. Here we examine two methods: one is to calculate the velocity from the derivative of range, and the other is to calculate flow directly from the FFT of the echo.

Here we report on a simple experiment to measure the motion of an object with a well understood model. This enables us to compare the measurements with the theoretical trajectory. The swinging motion of a sphere hanging on the end of string can be approximately modelled as simple harmonic motion.

$$T = 2\pi\sqrt{\frac{l}{g}} \tag{16}$$

where T is the period of oscillation, l is the length of the string and g is the acceleration due to gravity. A 100mm diameter, 236 gram sphere hanging on a 2 meter string (from attachment point to centre of sphere) has an expected period of 2.83845 seconds.

This sphere was hung from the ceiling in front of a K-Sonar sensor, so that it remained within the main lobe while swinging. Every 100 msec an echo was recorded over a period of 6.4 seconds (2.2 times the expected period). Simple harmonic motion is defined by the equation

$$x(t) = A\cos(\omega t + \phi) \tag{17}$$

The range readings for a swing with an amplitude of 0.3 meters are shown in Fig. 5. The period of this wave is 2.9 seconds showing good equivalence with the expected value. Also, the curve approximates a cosine function.

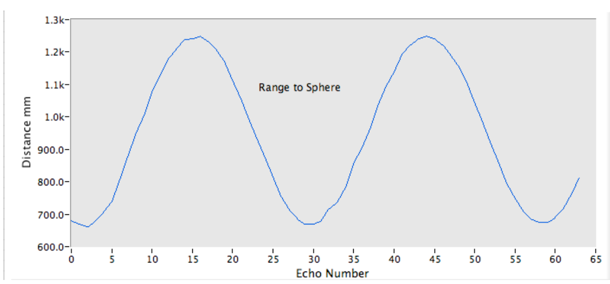

Fig. 5. Range to swinging sphere – echoes recorded every 100 msec.

The expected velocity of the sphere is the derivative of Equation 17, that is a sine wave (Equation 18) where velocity leads position by 90°.

$$v(t) = -A\omega\sin(\omega t + \phi) \tag{18}$$

From the graph in Fig.5. the period is 2.9 seconds and the amplitude is 0.3 m, giving a maximum velocity of 0.65 m/sec. One way to calculate the velocity curve is the difference between the range readings at successive time steps, i.e. by finite difference mathematics. The result of this calculation for the measured swing of the sphere is shown in Fig. 6. The measured velocity curve leads the position curve by 90°, has some noise and peaks at the predicted velocity.

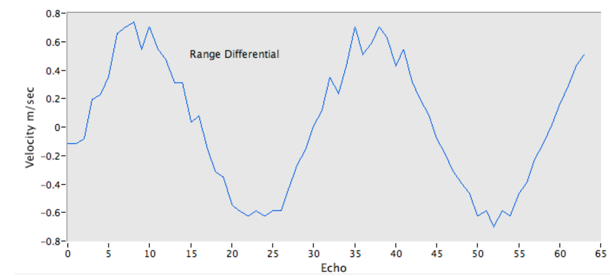

Fig. 6. Velocity of the sphere calculated by range/frequency differential.

The above calculation requires the extraction of the range from 2 echoes before the velocity can be calculated. If we can calculate the velocity from one echo we are closer to our concept of acoustic flow. A way to calculate frequency change [7] is to calculate the frequency difference from the leakage of the FFT caused by the frequency variation.

We hypothesized that the leakage can be measured by measuring the width of the echo, which is frequency change per 100msec. Observation of the echo indicated that the width does vary with velocity with the maximum width near middle of the swing (Fig. 7.).

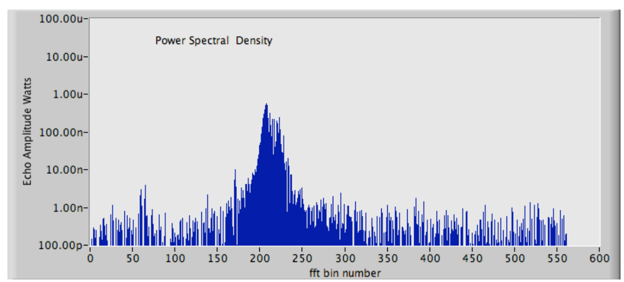

Fig. 7. Power spectral density of the last echo from the sphere swinging in Fig. 5. showing a very wide echo.

However, calculation of the width of the echo as the count of FFT lines above a fixed threshold produces very interesting results (Fig. 8.) that we are still analysing. The width calculation is shown as the solid line in Fig. 8. in comparison to the velocity calculated by range difference from Fig. 6. (dashed line).

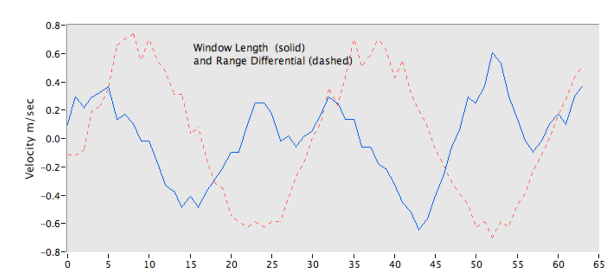

Fig. 8. Velocity of sphere, calculated from window width (solid line) and range difference (dashed line).

The velocity calculated from the width of the echo is very different to the velocity calculated from the range differential. There is a phase shift and the maximum peak has a dip in it. A similar shaped curve (Fig. 9.) can be obtained from an equation with the general form:

$$v(t) = -\sin(\omega t) + \sin(\omega t)^2 \quad (19)$$

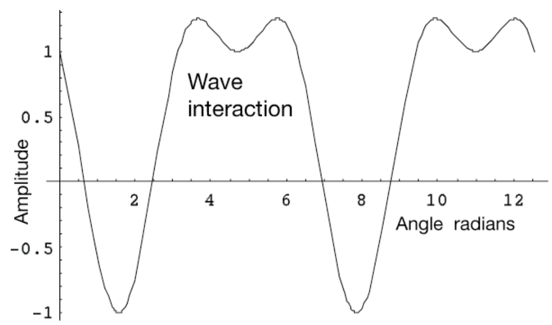

Fig. 9. Plot of Equation 19 showing a general form similar to the velocity calculated from window width (Fig. 8.).

The two factors that may multiply together to cause the above are a cyclic variation in both echo amplitude and Doppler shift with range. Amplitude variation with range (Fig. 10.) means that using a fixed threshold is not the correct way to measure echo width.

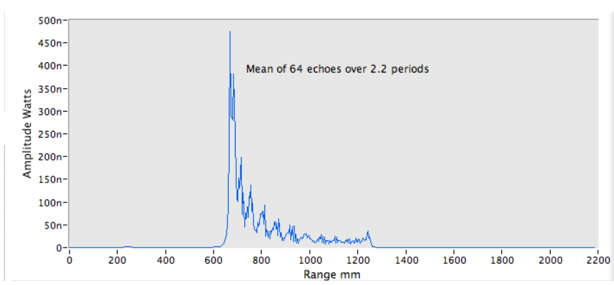

Fig. 10. Mean of the 64 echoes showing amplitude attenuation with range.

VII. Conclusion

Acoustic flow is a real physical phenomenon that we can observe with a CTFM ultrasonic sensor. In this paper, we have discussed the concept of acoustic flow, started along the path to the development of a theory, and evaluated it with a simple experiment.

In that experiment, an ultrasonic sensor measured the range to a swinging ball. Initial analysis indicates that it will be possible to measure the velocity of the ball from the echo once the impact of amplitude attenuation with range and Doppler shift is taken into account.

Acoustic flow provides a new conceptual framework for thinking about measuring motion with ultrasonic sensing, just as optic flow did for vision. As with optic flow, moving from concept to theory requires experimental work.

The measurement of acoustic flow may provide mobile robots with a new perceptual ability: the ability to track and analyse the motion of moving objects. This ability would enable them to navigate through dynamic environments to perform real-world tasks.

Acknowledgment

We wish to thank Em. Professor Leslie Kay for sharing his insights into the experiences of blind people using the Kaspa and K-Sonar CTFM mobility aids. The K-Sonar sensor used in this research was supplied by Bay Advanced Technologies of New Zealand.

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