ULTRASONIC PULSE SCATTERING BY FISH MUSCLE
WITH APPLICATIONS TO QUALITY INSPECTION

by

MANFRED FREESE

A THESIS

SUBMITTED TO THE FACULTY OF GRADUATE STUDIES

IN PARTIAL FULFILMENT OF THE REQUIREMENTS FOR THE DEGREE

OF DOCTOR OF PHILOSOPHY IN ELECTRICAL ENGINEERING

DEPARTMENT OF ELECTRICAL ENGINEERING

UNIVERSITY OF MANITOBA

WINNIPEG, MANITOBA

CANADA

OCTOBER 1974

ULTRASONIC PULSE SCATTERING BY FISH MUSCLE

WITH APPLICATIONS TO QUALITY INSPECTION

by

MANFRED FREESE

A dissertation submitted to the Faculty of Graduate Studies of the University of Manitoba in partial fulfillment of the requirements of the degree of

DOCTOR OF PHILOSOPHY

It may be a weed instead of a fish that, after all my labour, I may at last pull up.

Michael Faraday

ACKNOWLEDGEMENTS

The author would like to thank Dr. M. A. K. Hamid, Dr. E. G. Bligh and Dr. W. E. Johnson for their encouragement and support during the course of this work. For Dr. Hamid's assistance in the reviewing and editing of the text, the author is particularly grateful.

The assistance provided by H. Ballon in performing many of the measurements is greatly appreciated, as is the co-operation of members of the analytical chemistry group of the Freshwater Institute in performing biochemical analyses, and Dr. D. P. Scott and B. Hobden in advising and assisting in the histological aspects of the work.

The author wishes to express his deep appreciation to his wife, Barbara, for her patience and forbearance, and for the typing of a rather difficult manuscript.

Finally, the author would like to thank the Fisheries Research Board of Canada for granting him a leave of absence and supporting the research project.

ABSTRACT

This dissertation presents the results of an investigation of the origin and characteristics of ultrasonic volume backscatter in the 1 to 5 MHz frequency range from fish muscle tissue as a function of the tissue composition and condition. Scattering by the tissue structural components is analyzed with particular emphasis on scattering by rough interfaces and thin membranes. A fairly detailed physical optics treatment for scattering by a rough surface of low reflectance is presented in this connection. In the context of this work the problem of in situ diagnostic pulse backscatter measurements for soft animal tissues is examined both theoretically and experimentally. Various aspects, including the effects of absorption, pulse bandwidth and scatterer response, are discussed and analyzed. The problem of calibration, the derivation of a backscatter coefficient and the use of broadband beam near-field measurements are also examined.

The tissue measurements are restricted principally to the lateral myomere of lake whitefish (Coregonus clupeaformis), a fatty species, and pickerel (Stizostedion vitreum), a lean species. However, additional measurements on model media of air and oil bubble suspensions, tissue structural components and bovine muscle are included for comparison.

It is found that the backscatter from whitefish muscle (transverse incidence with respect to the muscle fibers) in the frequency range of 2.3 to 4.8 MHz generally varies as $\lambda^{-2.4}$, where λ is the wavelength, compared to $\lambda^{-1.3}$ for pickerel and $\lambda^{-2.4}$ for a sample of bovine

skeletal muscle. The results are interpreted with the aid of theoretical calculations based on a first order statistical scattering model of the fish tissue, histological observations and measurements of the model media. The $\lambda^{-1.3}$ dependence for pickerel appears to be due primarily to scattering by the muscle fibers and the myosepta.

It is shown that, if the tissues are free of gas bubbles, lipid inclusions are usually the dominant scatterers in whitefish; for total lipid contents up to 6%, a roughly linear relationship between the backscatter intensity and the lipid content is observed. However, it is also shown that, as a result of decompression, gas bubbles are almost invariably present in whitefish, in which case these tend to be the predominant scatterers.

In addition to the system modelling of the composite tissue scattering process and the ultrasonic characterization of fish tissue, the results are of significance towards the development of practical ultrasonic inspection and/or quality control techniques in the fishing industry, as well as other segments of the food processing industry. The results may also be valuable for the development of ultrasonic diagnostic techniques in the biomedical field.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

CHAPTER 1

INTRODUCTION

The need for better methods of objective evaluation and inspection of quality in the processing and marketing of fish is widely recognized [Stevenson & Kellogg, Ltd. (1970)]. Although much progress has been made in identifying and isolating the factors affecting quality [FAO (1964), (1969)], adequate means of grading and inspection are still lacking in many important areas, particularly where rapid, non-destructive testing applicable in situ is a key consideration. One such area is that of inspection for parasites. The occurrence of these intramuscular parasites in many economically important species (e.g. whitefish and cod) constitutes a grave problem in the industry [McIvor (1965); Stevenson & Kellogg, Ltd. (1970); FAO (1969)]. Work on the detection of these parasites by means of ultrasound [Freese (1969)], particularly Triaenophorus crassus in whitefish, showed that a pulse-echo technique was feasible but was hampered by tissue scattering. Preliminary work on the ultrasonic properties of tissue [Freese and Makow (1968.a.b)] suggested that ultrasonic techniques might also be exploited for quality control and inspection purposes in other areas, for example, to distinguish fresh and frozen-thawed tissue and to determine the fat content of round fish.

For the development of such methods and optimization of the parasite detection process, a knowledge of the tissue backscatter characteristics under all possible conditions is required. Although considerable experimental data on the ultrasonic propagation parameters for biological media is available [El'piner (1964); Dunn et al. (1969)], including fish tissue [Haslett (1962); Freese and Makow (1968.b); Matsui and Shibata (1971)], it was found that quantitative data on the scattering properties of fish, as well as of soft animal tissues generally, is presently lacking. In respect to human tissue, for example, Hill (1972), in a recent paper given at the Workshop Conference on the Interaction of Ultrasound and Biological Tissues, observed

> "....very little indeed is known in quantitative terms about the backscattering properties of human tissues, and virtually nothing about their frequency dependence."

Until recently [Aldridge and Tattersall (1971); Szilard and Scruton (1973)], there has been little apparent effort made in exploiting ultrasonic diffuse scattering for industrial, non-destructive testing applications. Although ultrasound is widely used, with few exceptions the methods rely on specular pulse reflection, absorption and velocity. Similarly in the biomedical field, where ultrasound is widely used for visualization purposes, few attempts have been made to investigate and measure scattering by different biological tissues in a quantitative sense until recently [Senapati et al. (1972); Waag and Lerner (1973)], although its potential for characterizing the structure of tissues has certainly been recognized [e.g. Wild and Reid (1953); Reid and Sikov (1972)].

The lack of progress in the development of scattering methods is not hard to explain. In the case of many industrial applications, where the sample to be tested is readily accessible and has a well-defined geometry, absorption and velocity can generally be determined more easily and accurately than the scattering properties. In addition, the development of satisfactory diagnostic scattering procedures in both the industrial and biomedical sectors has generally been deterred by obstacles such as lack of accuracy, ambiguities in the results, high reverberation levels due to intervening interfaces (as, for example, in echoencephalography), the presence of moderate to high attenuation in the tissues and theoretical and experimental difficulties due to the complex nature of the scattering media.

To obtain a proper perspective of these obstacles and to furnish a realistic model for the development of fish inspection techniques and hardware, a detailed analysis of the tissue backscatter problem is necessary.

In this dissertation we present the results of an investigation of volume backscatter from fish tissues in the 1 to 5 MHz range, and we consider the problem of pulse backscattering by soft tissues for in situ applications. The origin and characteristics of the backscatter are examined theoretically and experimentally, and are correlated with the overall composition and condition of the tissues. Although the measurements are restricted principally to the lateral myomere of lake whitefish (Coregonus clupeaformis) and pickerel, also known as walleye (Stizostedion vitreum), some measurements on model media and bovine muscle are included for purposes of comparison.

The theoretical work falls broadly into two categories. The first is concerned with the analysis of the different scatterers found in fish tissues, and also to some extent in other animal tissues. The objective may be summed up as an attempt to estimate the magnitude and wavelength dependence of the backscatter by the various tissue inhomogeneities. In spite of the fact that we have specifically referred to volume scattering, a significant portion of the scattering in both mammalian and fish tissues may be from thin membranes and organ interfaces intersecting the insonified volume. In the case of fish muscle, a regular series of involuted thin membranes bind the muscle segments that give fish muscle its distinctive chevron-shaped appearance. These membranes or tissue sheets are usually far from smooth at millimeter wavelengths and may have characteristic impedances significantly different from those of the surrounding tissues. Scattering from rough surfaces and thin membranes is thus given major emphasis and a fairly comprehensive first order treatment is presented.

The other part of the theoretical work is concerned with the analysis of the actual measurement problem. A phenomenological view of the stochastic scattering process due to Faure (1964), Ol'shevskii (1967) and Middleton (1967), (1972) is adopted and a model of the tissue scattering process is derived. The resultant model greatly facilitates the analysis of the scattering process by illustrating in a straightforward manner the influence of the various scattering medium parameters and those of the measurement setup. It is thus valuable in the design and optimization of new diagnostic systems. Various aspects of the scattering process, including the statistical properties, the effects of absorption, the signal pulse characteristics and measurements in the transition region between the near and far fields, are analyzed and compared with the results of experiments.

1.1 Background and Approach

Of the two fundamental roles of scattering mentioned in the introduction, the inverse scattering problem represents by far the more difficult problem. As in the case of the forward (input-output) problem,[1] two basic techniques are commonly employed in the solution of the inverse problem. The first of these attempts to directly invert the problem, while the second approach employs a comparison method and might therefore be more properly termed pseudo-inverse. Frequently these two methods are combined. We shall employ the latter method which in its essential features is similar to regression analysis. Unfortunately, as in the case of regression analysis, or to use the analogy of a black box from circuit theory, two boxes may be equivalent at particular frequencies but the contents are not necessarily identical. This lack of uniqueness underlines the fact that, although in principle scattering measurements can reveal a great deal about the structure of a medium, in practice additional information derived from other sources is required if the analysis of the scattering is to yield useful results.

1.1.1 Scattering Techniques

In applications where anisotropy and geometry are not a problem, some of the bistatic scattering techniques used in optical and microwave studies [Van De Hulst (1957); Kerker (1969); Wheelon (1959); Beckmann and Spizzichino (1963)] may be employed to advantage. Thus, Senapati et al. (1972) examined rough surface scattering as a function

---

[1] Rigorous solution of the relevant statistical wave or diffusion equation versus Monte Carlo methods.

of frequency and angle from frog muscle and liver tissues. However, in general bistatic measurements are difficult to perform in the case of scattering from tissue volumes or embedded surfaces because of interference by strong reflections from the outer surface. For inspection applications of deep-lying tissues in situ only monostatic volume scattering measurements can normally be considered. This entails some loss of information but it should be remembered that due to the absence of polarization effects, bistatic acoustic compressional wave scattering measurements yield comparatively less information than do analogous electromagnetic and optical measurements [Van De Hulst (1957)]. Nonetheless, it is clear that this aggravates the problem of measurement ambiguities further. Depending on the nature of the application and of the ambiguities, be it number, size and shape distribution and/or composition of the scatterers, the backscatter measurements may have to be supplemented by additional information regarding the medium.

In some cases it may be possible to obtain this information by other ultrasonic measurements, for example, absorption and velocity, but just as often this proves impractical and some other means have to be found.

1.1.2 Scattering by Random Media

Two principal lines of attack towards the solution of random scattering problems are evident. The first of these is via the wave equation for inhomogeneous media or the equivalent integral equation. The inhomogeneous wave equation has the form

$$\nabla^2\Psi(\vec{r}) + k^2\Psi(\vec{r}) = q(\vec{r}) \tag{1.1.1}$$

where $\Psi(\vec{r})$ is the velocity potential and $q(\vec{r})$ represents the sources. In regions of variable compressibility and/or density which constitute the inhomogeneites (bulk scatterers) in the medium, $q(\vec{r})$ will differ from zero giving rise to scattering of the incident waves.

Foreign bodies which scatter the sound (surface scatterers) are usually more easily treated in terms of an integral equation equivalent to (1.1.1). For an incident plane wave $\Psi_i(\vec{r}) = e^{jk\vec{r}-j\omega t}$, one obtains [Morse and Ingard (1968)]

$$\Psi(\vec{r}) = \Psi_i(\vec{r}) + \sum_j \iiint_{V_j} G(\vec{r}|\vec{r}_o)\ \chi(\vec{r}_o)\ \Psi(\vec{r}_o)\ dv_o + \sum_\ell \iint_{S_\ell} \left[\Psi(\vec{r}_o)_s \frac{\partial G(\vec{r}|\vec{r}_o)}{\partial n_o} - G(\vec{r}|\vec{r}_o) \frac{\partial \Psi(\vec{r}_o)}{\partial n_o}\right] ds_o \qquad (1.1.2)$$

where $G(\vec{r}|\vec{r}_o)$ is the Green's function, $\chi(\vec{r}_o)$ is the strength of the local inhomogeneity, $\Psi(\vec{r}_o)$ is the local velocity potential and $\vec{n}_o$ is the local surface normal.

Several approximation techniques (ibid.) have been developed for evaluating either (1.1.1) or (1.1.2). Among the best known is the Born approximation technique obtained by substituting $\Psi_i(\vec{r}_o)$ for $\Psi(\vec{r}_o)$ in (1.1.2) and then iterating to obtain the n-tuply scattered waves $(n > 1)$.

The first order Born approximation will be valid only to the extent to which interaction of the scatterers including 'self-interaction' via the scattered field may be neglected. This implies that the scattered field be much smaller than $\Psi_i(\vec{r})$.

The statistical properties of the scattering may be found by solving (1.1.1) or (1.1.2) for specified space-time statistics of the scattering inhomogeneities. However, evaluation beyond the first Born approximation is generally difficult, even in those few cases where simple analytical statistical parameter distributions such as the Gaussian distribution may be applicable. We shall use the Born approximation to evaluate scattering by a rough sheet in Chapter 2.

The alternate approach assumes that the scattering results from equivalent discrete scatterers (in effect point-scatterers or scattering centers) located randomly throughout the volume (or on the surface) of the insonified medium. The scattering centers are essentially mathematical fictions but take on a certain physical reality when the impedance discontinuities are sufficiently sharply defined. Thus, air bubbles with dimensions less than the ultrasonic wavelength are rather well approximated by discrete scatterers. Larger scatterers may sometimes be represented by an aggregate of scattering centers physically identifiable as the specular flare points, diffracting edges and points of the scattering obstacle. The point-scatterer approach is thus conceptually closest to the geometrical theory of diffraction of Keller (1953).

The stochastic nature of the scatterers may be taken into account by direct averaging over the scatterer statistical parameters or by an equivalent very general procedure of averaging over the random configurations of the scatterers consistent with the statistical information available. This method of statistical averaging was introduced by Foldy (1945) to treat n^{th}-order multiple scattering from random scatterers. When used in conjunction with the wave equation approach, this technique leads to the stochastic forms of the wave equation (1.1.1) and (1.1.2).[1]

The point-scatterer theory has been greatly developed in the field of underwater acoustics within recent years by Faure (1964), Ol'shevskii (1967) and Middleton (1967). The latter author, in particular, has applied this method to some very complex reverberation problems [Middleton (1972)].

What makes the point-scatterer approach so attractive is the ease with which various characteristics of the medium and the measurement system can be introduced. Thus, even if the impulse responses of the point-scatterers are not initially specified making it impossible to calculate the actual backscatter level, the scatterer model can still be used to analyze the influence of the measurement system and medium parameters on the statistical parameters that characterize the resultant scattering. With the impulse response specified, the point-scatterer theory becomes a convenient vehicle for implementing the analysis of the pseudo-inverse scattering problem. We shall make use of the point-scatterer theory in both of these contexts.

1.2 Résumé

A brief review of the structure and composition of skeletal muscle tissue outlining the similarities and differences of mammalian

---

[1]Details of this procedure and conditions for the validity of the method, including an examination of the fundamental problem of n^{th}-order random multiple scattering--the lack of completeness, may be found in a paper by Waterman and Truell (1961); see also various papers by Twersky (1962, 1963).

and fish muscle is given at the beginning of Chapter 2. The chapter, however, is devoted mainly to a theoretical analysis of the scattering cross-sections of the various fish tissue inhomogeneities, although some experimental data is introduced to delimit and simplify the analysis. A major part of the chapter deals with scattering by rough surfaces and thin membranes. Scattering by rough interfaces of low reflectivity (normalized characteristic admittance near unity) is analyzed using a slightly modified form of the physical optics solution due to Beckmann and Spizzichino (1963). The results are then applied to a heuristic treatment of scattering by a rough thin sheet and generalized for narrow-beamwidth and short pulse incidence. At the end of the chapter a working definition for the pulse backscatter coefficient is given which serves as the principal basis for reporting of the experimental scattering results.

A composite model of the tissue volume backscatter process based on the Middleton-Ol'shevskii point-scatterer theory is developed in Chapter 3. Elementary statistical and signal processing concepts are reviewed and expressions for the first and second moments are derived, together with suitable first order corrections for the effects of absorption and finite bandwidth.

The significance of the pulse bandwidth in terms of the transmitter-receiver bandwidth, the effects of absorption, and the resultant modifications in the scattering and near-field distributions are examined in some detail. The latter is illustrated by a number of comparisons of experimental near-field and transition region pulse measurements with theoretical CW and wideband data. The use of these measurements in the case of in situ measurements is then considered from a practical standpoint and various advantages and disadvantages of such measurements are outlined.

Chapter 4 describes the experimental methods and instrumentation used in the measurements. Important data is given on the beam and pulse parameters, the reference calibrations and the various transducer and instrument characteristics. The determination of the near- and far-field equivalent insonified volumes is discussed and the results are compared with theory. Also described in this chapter are the different techniques employed to measure ultrasonic absorption and velocity and the methods used to determine the various other tissue properties of interest.

In Chapter 5 the results of backscatter measurements are presented. The first section of the chapter is devoted to an investigation of the backscatter from a model medium of gelatin containing air bubbles for the purpose of verifying the basic experimental approach and the calibration of the setup. The results are compared with first order scattering theory. The volume backscatter as a function of frequency from the lateral muscles of whitefish and pickerel is then analyzed and interpreted in terms of the characteristics of the known inhomogeneities considered in Chapter 2. Further evidence in the form of experimental measurements on model media of gelatin and oil bubbles and measurements from excised pinbones and myosepta is given and compared with the results of theoretical calculations.

The dependence of backscattering on the tissue composition, the measurement conditions and the nature of the fish is investigated. Other aspects examined are the problem of gas bubbles in the tissues