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# Spatio-Temporal Characterization of Bio-Acoustic Scatterers in Complex Media

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## LONG TERM GOALS

To develop a methodology for extracting the relevant spatial and temporal scales of bio-acoustic scatterers based on multi bi-static long-range measurements in shallow water waveguides.

## OBJECTIVE

Characterization of biologically-induced ocean reverberation features is key to effectively parametrize acoustic models and thus ultimately improve the detection performance of long-range SONAR systems. In particular, scattering from fish schools can significantly contribute to volume reverberation in the open ocean measured by mid-frequencies tactical SONAR (1kHz-10kHz), especially if the resonance frequencies of the fish' air-filled swim bladder is excited. Furthermore, multiple scattering effects from the incident acoustic wave and the collective arrangement of fish lead to complicated frequency response functions. The bio-acoustics properties of the fish body and geometry can also contribute to the scattering response and can be incorporated into an accurate scattering model.

The objective of this research is to characterize the relevant *spatial and temporal scales* of bio-acoustic scatterers generating ocean reverberation to effectively parametrize acoustic models and improve the detection performance of long-range SONAR systems. To do so, we will first develop an efficient modeling technique predict the scattered fields from large fish schools (which can cause especially high false-alarm rate for mid-frequency SONAR systems.), which readily account for the fish acoustic properties, school's spatial configuration and multiple scattering effects.

***Fig. 1 School of  Fuseliers fishes (Papua New Guinea), photo by Randy Harwood.***

**WORK  COMPLETED**

Two key observations can be made about large fish schools. First, in large schools, fishes typically swim in a *periodic* arrangement where fishes are regularly spaced by approximately one-body length in all three dimensions (see Fig. 1). Second large fish schools (e.g. several km wide) can have dimensions exceeding several thousand of wavelengths of the SONAR's frequency. Hence, based on these two observations, we will treat large fish schools as an *infinitely* system generated by tessellating in 3D a unit volume cell containing a single fish (e.g. see Fig. 2). This infinite system can be modeled as a periodic phononic crystal which is a special class of well-studied periodic materials that support acoustic or elastic waves. In our case, the infinite phononic fish crystal (FC) contains a host medium (homogenous, quiescent water) and periodically spaced inclusions (fish bodies).  The infinite phononic fish crystal (FC) contains an infinite set of mode shapes, with corresponding natural frequencies, analogous to a finite vibrational system. Arising from the infinite number of multiple scattering events the FC exhibits Bragg scattering phenomena as well as complete band gaps where acoustic waves are *prohibited* from propagating in the crystal [1]. The Bloch theorem, which accounts for *all orders* of multiple scattering, is employed to calculate the frequencies and modes of the infinite fish crystal.

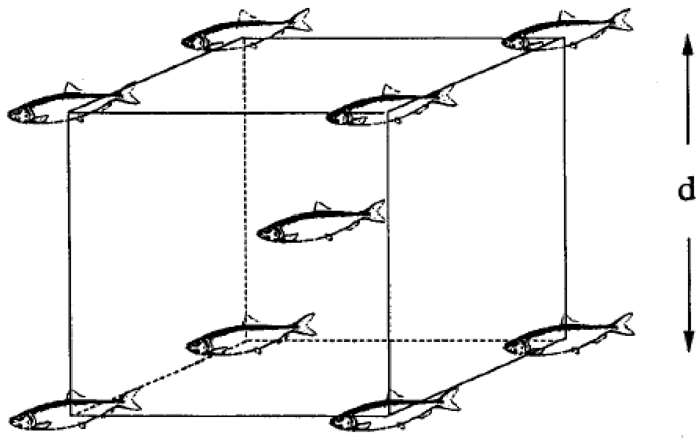


***Fig. 2 A basic school unit. The schools are constructed from cubic cellular units (or unit cell). The packing density is determined by the distance d between closest neighbors [Reproduced from Feuillade et al., J. Acoust. Soc. Am. 99 (1),1996].***

In a 2D periodic lattice the pressure $p(\mathbf{r},t)$ at any field point $\mathbf{r}=\tilde{\mathbf{r}}+\mathbf{R}$ can be represented using the Bloch theorem (assuming harmonic time dependence $-i\omega t$) by

$$p(\mathbf{r},t)=p(\mathbf{r})\exp(-i\omega t)=\tilde{p}(\tilde{\mathbf{r}})\exp\left(i\left(\mu_1 m+\mu_2 n-\omega t\right)\right) \tag{1}$$

where $\mathbf{R}=m\mathbf{a}_1+n\mathbf{a}_2$ is any lattice vector with integer $m,n$ , $\tilde{\mathbf{r}}$ is a vector inside the unit cell, and $\tilde{p}(\tilde{\mathbf{r}})=\tilde{p}(\tilde{\mathbf{r}}+\mathbf{R})$ is a periodic wave function. The phase constants $\mu_1=k_1a_1,\ \mu_2=k_2a_2$ , $-\pi\le\mu_1,\mu_2\le\pi$ are defined for brevity and the quantities $k_1,\ k_2$ represent the wave numbers of the global *Bloch wave* $\tilde{p}$ and it is noted that $k_1,\ k_2\ne k=\omega/c$ [2]. The unit cell has dimensions $a_1,a_2$ in the $x$, $y$ directions.

To solve for the modal response we begin by constructing a finite element mesh on a periodic unit cell (e.g .see Fig. 2). Standard finite element discretization techniques of the Helmholtz equation $\left[\nabla^2+(\omega/c)^2\right]p=0$ (sound speed $c$) result in mass and stiffness matrices $\mathbf{M}$, $\mathbf{K}$ and a nodal solution vector $\mathbf{q}$ . Invoking the Bloch theorem [3] results in an eigenvalue problem for frequency $\omega$ parameterized by the phase constants $\mu_1,\mu_2$

$$\left[-\omega^2(\mu_1,\mu_2)\tilde{\mathbf{M}}(\mu_1,\mu_2)+\tilde{\mathbf{K}}(\mu_1,\mu_2)\right]\tilde{\mathbf{q}}=0 \tag{2}$$

where the tilde represents matrices and vectors representative of the unit cell. Solution of (2) enables the determination of the dispersion relation for the eigenvalue $\omega(\mu_1,\mu_2)$ and the eigenvector $\tilde{\mathbf{q}}\to\tilde{p}(\tilde{\mathbf{r}})$ The matrices in (2) embody the discretization of any periodic cell with a complex shape, material properties, etc. To reiterate: the acoustic field inside an infinite lattice of fish air bladders can be computed by employing the Bloch theorem (1) and the solution to the parameterized eigenvalue problem of (2); this solution accounts for all wave scattering.

A dispersion relationship $\omega(\mu_1, \mu_2)$ has been obtained for a 2D infinite fish crystal with realistic physical properties [4]. The unit cell consists of water as the host material with cell dimensions (lattice constants) $a_1 = a_2 = 40$ cm, an inviscid flesh fish body of density $\rho = 1050\,\mathrm{kg/m^3}$, speed $c = 1550\,\mathrm{m/s}$, and radius 12 cm, and an air bladder with radius 2 cm. The lattice constant of 40 cm is a typical body length which is approximately equal to the fish spacing. The geometry and the computed dispersion relationship is displayed in Fig. 3. Note the existence of the band gap (colored box) whereby a propagating Bloch wave is not allowed; only an evanescent wave exists. To computationally verify the pressure field of a finite lattice using the Bloch modes of an infinite system, a 2D finite element simulation was developed with a plane wave incident on a row of 20 air bladders with water as the host material, shown in Fig. 4. In Fig. 5 excellent agreement is observed between the horizontal centerline pressure variation of the finite lattice and the infinite Bloch mode.

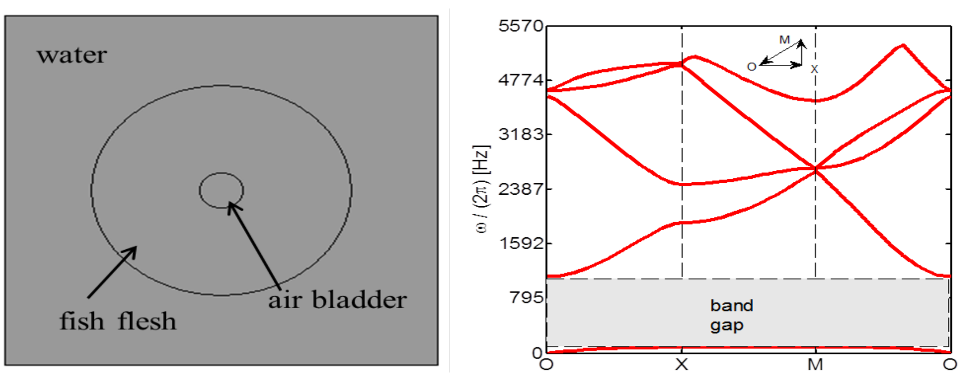


***Figure 3. Geometry (left) of 2D fish unit cell and the dispersion relationship (right) of the infinte fish crystal. Note the existence of a band gap (colored rectangle) whereby there exists no propagated wave in the FC***

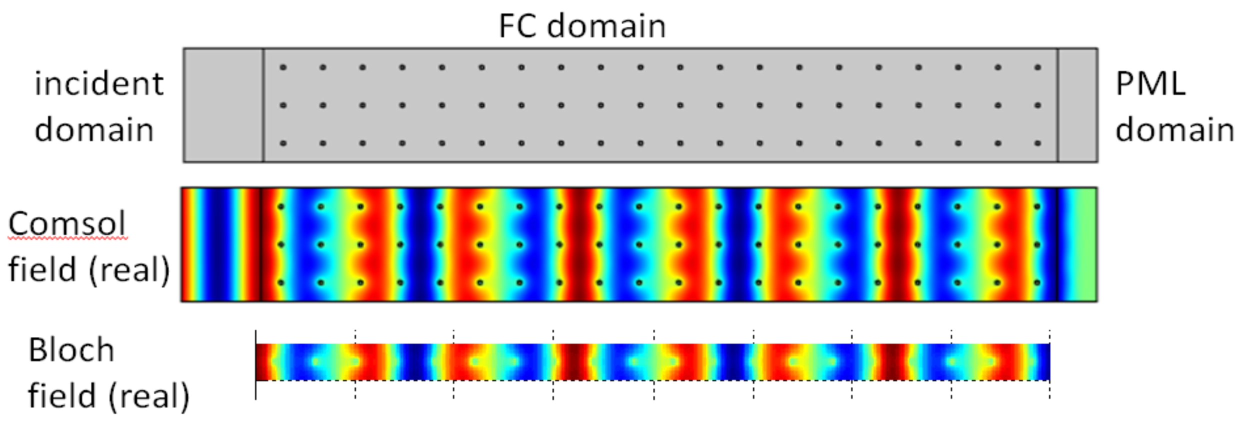


*Figure 4. Computational finite element model (top). Predicted pressure field using COMSOL which requires discretization of the full computational domain (middle). On the bottom is the equivalent Bloch field, which only required discretization of single unit cell (denoted by vertical dashed lines).*

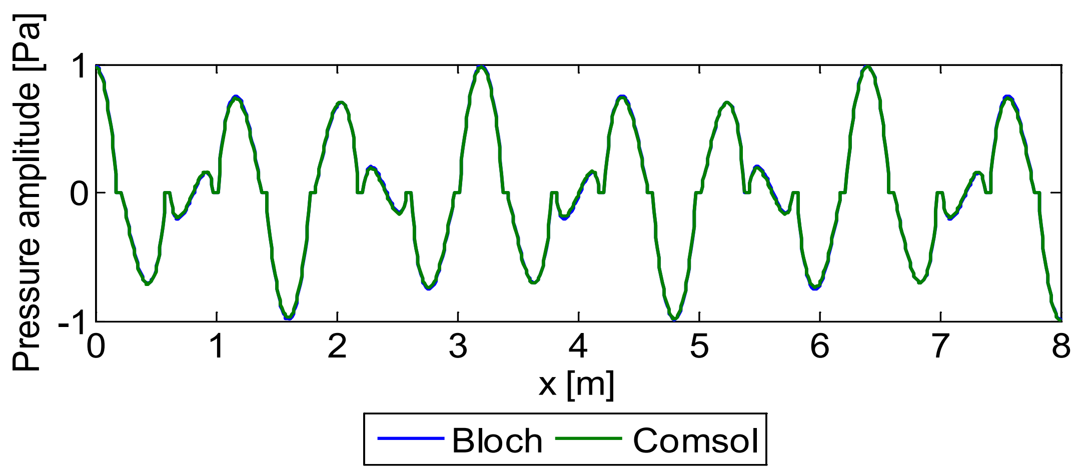


*Figure 5. Comparison of the real pressure field for the Comol finite element solution and the infinite Bloch solution. Measurement is made along the horizontal centerline from Figure 2.*

## CONCLUSIONS

The good agreement shown in Fig. 4 and Fig. 5 enforce the approximation of a large number of scattering bodies as an infinite periodic system amenable to Bloch analysis. Furthermore, the computational cost for the Bloch analysis (which models only a single unit cell) is significantly reduced compared to the COMSOL Finite Element model of the full domain with multiple unit cells. Future work will focus on further validation of the infinite approximation using Bloch eigenmodes including calculation of the scattered field. The proposed approach will be extended to predict the scattered response realistic three dimensional large fish system of finite size.

## IMPACT

It is conjectured that the results of this study could potentially be used to reduce the uncertainty of SONAR prediction modeling tools due to marine biota, thus ultimately improving the remote detection, classification and localization of marine bioata using long-range mid-frequency SONAR systems.

## REFERENCES


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