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Turbulent flow due to the interaction of two mutually perpendicular crossed turbulent streaming jets in water

--Manuscript Draft--

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Abstract:	The food industry has studied turbulent streaming from an ultrasonic horn reactor, where the turbulent flow field can be modelled by a laminar jet flow that has a turbulent eddy viscosity [M. J. Lighthill, “Acoustic streaming,” J. Sound Vib. 61 (3), (1978) 391–418]. Work by Kumar (2006), Trujillo (2009) and others successfully compared the results with CFD models, have sparked interest in revisiting turbulent streaming by an ultrasonic horn, resulting in this presentation. Our demonstration studies the turbulent flow generated by the interaction between two mutually perpendicular crossed streaming jets – which both exhibit turbulent behavior. We are specifically interested in the flow field in the forward and backward directions defined by the bisecting line segment ±45 degrees from the axis of each streaming jet, with the line segment located in the plane shared by the jet axes. The apparatus consists of two Langevin ultrasonic transducers (125 kHz) that are both equipped with a half-wavelength exponential horn. The horns are slightly submerged in an open acrylic water tank to allow for viewing of the flow field. A particle image velocimeter (PIV) will be used to measure the turbulent flow velocity field in the plane of the interaction region aforementioned.
Section/Category:	Physical Acoustics

1. INTRODUCTION

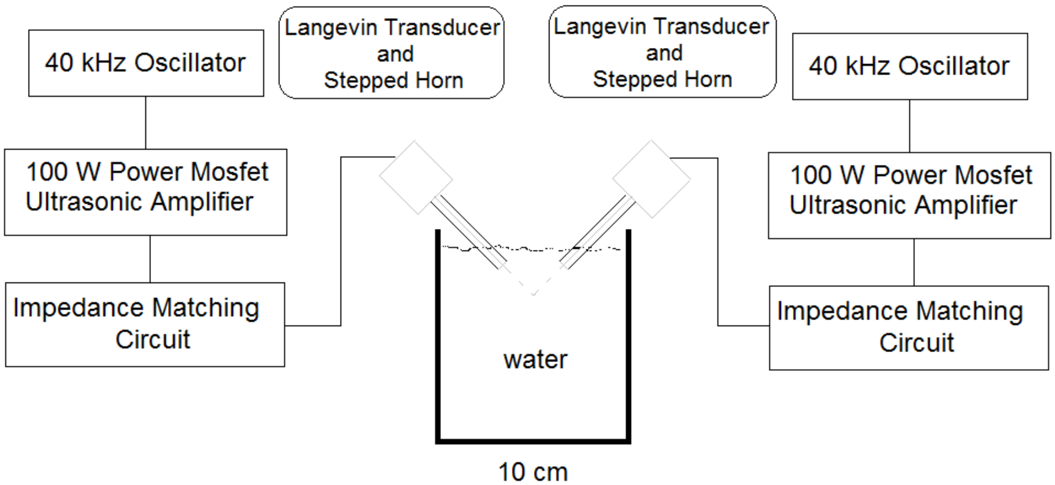

Figure 1. Experimental setup of the interaction of two mutually perpendicular crossed ultrasonic turbulent streaming jets in water.

The project goal was to perform an experiment involving two crossed ultrasonic turbulent streaming jets in water to observe the turbulent flow generated by their interaction. The experiment was performed in an open 10 cm cubic acrylic water tank. In sono-chemistry literature the apparatus might be called a stepped horn ultrasonic reactor. See Refs 11-15. Phase one of the research was to develop a Langevin transducer fastened to a stepped horn. In the next phase the Langevin transducer was fastened to a Gaussian horn. Next, a 100 Watt push pull MOSFET ultrasonic amplifier was designed, built, and tested in the physical acoustics lab at U. S. Naval Academy. The original designs used a Langevin transducer that operated at the third overtone of the fundamental 40 kHz frequency, which is 120 kHz. The stepped horn and exponential horn tapered down from roughly 2 in diameter to ½ in diameter over a half wavelength. Here, the longitudinal wave speed in the aluminum material (which made up the horn) was around 5112 m/s. Experiments performed at f = 120 kHz with the transducer and horns generated some acoustic streaming, however, the streaming was not turbulent. The authors realized that the system was not optimal and decided to use a commercially available system.

Figure 1 shows the experimental setup of the crossed ultrasonic turbulent streaming jets in water. Here, a 40 kHz oscillator is amplified by a 100 Watt ultrasonic amplifier (Sonics & Materials KITVC 1022), which is impedance matched to the Sonics model (CV301) Langevin transducer and stepped horn (Part # 630-0422). Two such units are needed to generate the crossed ultrasonic turbulent streaming jets.

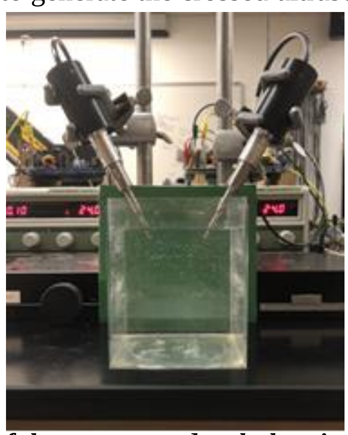

Figure 2. Photograph of the setup of the two crossed turbulent jets at roughly 60 degrees.

2. OVERVIEW – OUTLINE

(a.) The food industry and the sono-chemistry field have studied turbulent streaming from an ultrasonic horn reactor, where the average turbulent flow field can be modelled by a laminar jet flow that has a turbulent eddy viscosity see the work by J. M. Lighthill[10].

(b.) Work by Kumar[11, 12] in 2006 and 2007, Trujillo[13] in 2009 and others[14, 15] successfully compared horn reactor streaming with CFD (computational fluid dynamic) models.

(c.) In particular, work by Schenkar[14] in 2013 studied turbulent streaming using a 17.6 kHz, 4 kW ultrasonic horn of diameter 2.5 cm, with tip amplitude ~ 35 micro meters helped motivate our approach to the work presented here.

(d.) Our demonstration studies the turbulent flow generated by the interaction between two mutually perpendicular crossed streaming jets – which individually exhibit turbulent behavior. We are also interested in the flow field in the forward and backward directions defined by the bisecting line segment ±45 degrees from the axis of each streaming jet, with the line segment located in the plane shared by the jet axes. In our live demonstration at the 21st ISNA the authors showed crossed ultrasonic turbulent streaming jets at an angle of 60 degrees.

(e.) Our demonstration apparatus consists of two Langevin ultrasonic transducers (40 kHz) - both equipped with stepped horns with sections of diameters: 1/2, 1/4 and 1/8 inch (~ 12.7, 6.35, 3.18 mm). The ultrasonic power output for each sonotrode tip is on the order of magnitude 100 Watts. However, for the demonstration we used around 20 Watts of power for each stepped horn.

(f.) The horn tips are slightly submerged in an open acrylic rectangular water tank to allow for viewing of the flow field.

(g.) The demonstration result of the crossed ultrasonic streaming jets was videotaped as well as demonstrated live and some of the photographs from the demo are presented in this paper.

A. EARLY HOMEMADE PROTOTYPE APPARATUS

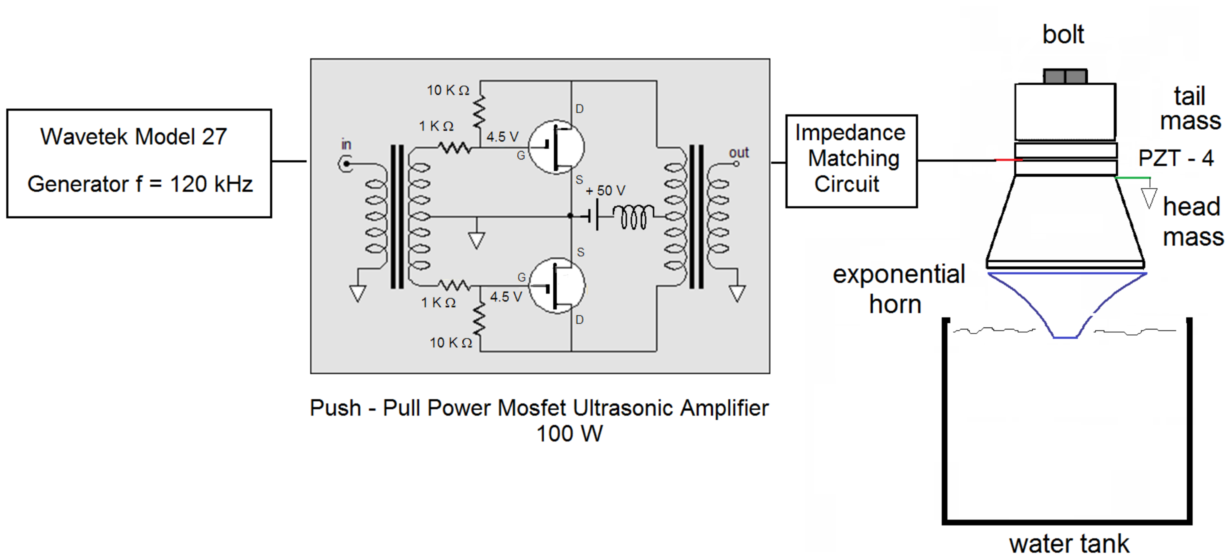

Figure 3. Early homemade prototype apparatus with half-wavelength exponential aluminum horn. Here, the large diameter is D_1 = 5 cm and the smaller diameter is D_2 = 1 cm, λ / 2 = 2.1 cm . The transducer is operating at the 3*40 kHz overtone, (namely 120 kHz). The open acrylic water tank is roughly 10x10x10 cm^3.

A photograph of the Langevin 120 kHz transducer is shown in Figure 4 below.

Figure 4. A commercially available Langevin ultrasonic transducer model SMBLTF120W60 used in Figure 3 above. A sandwich transducer is often called a Tonpilz transducer – meaning a singing mushroom.

3. EXPERIMENTAL SETUP AND RESULTS

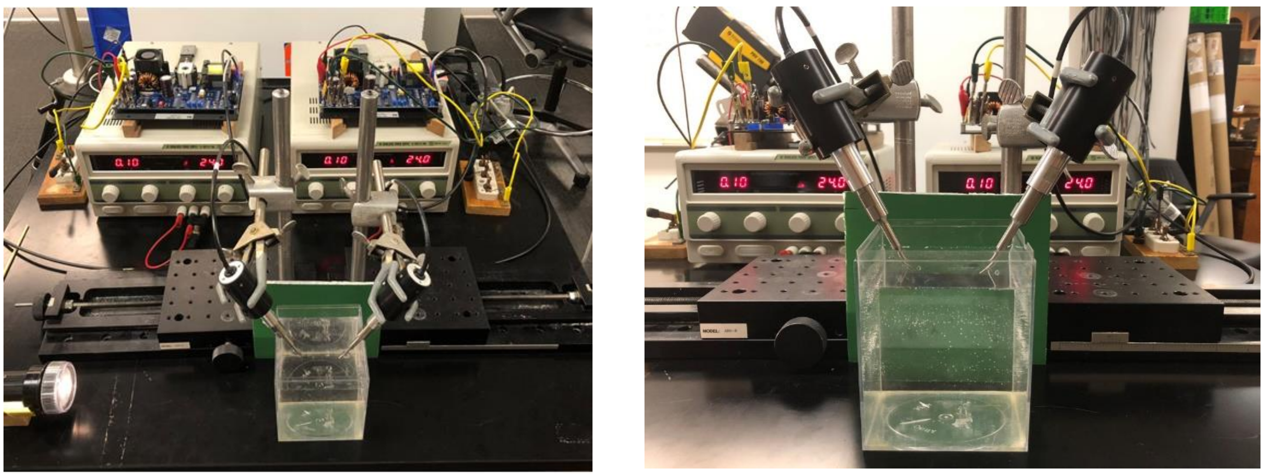

Figure 5. Complete experimental setup shows 24 volt power supplies, generator-amplifier circuit boards. Foreground: 40 kHz transducers with stepped horns slightly submerged in the open 10 cm square acrylic water tank.

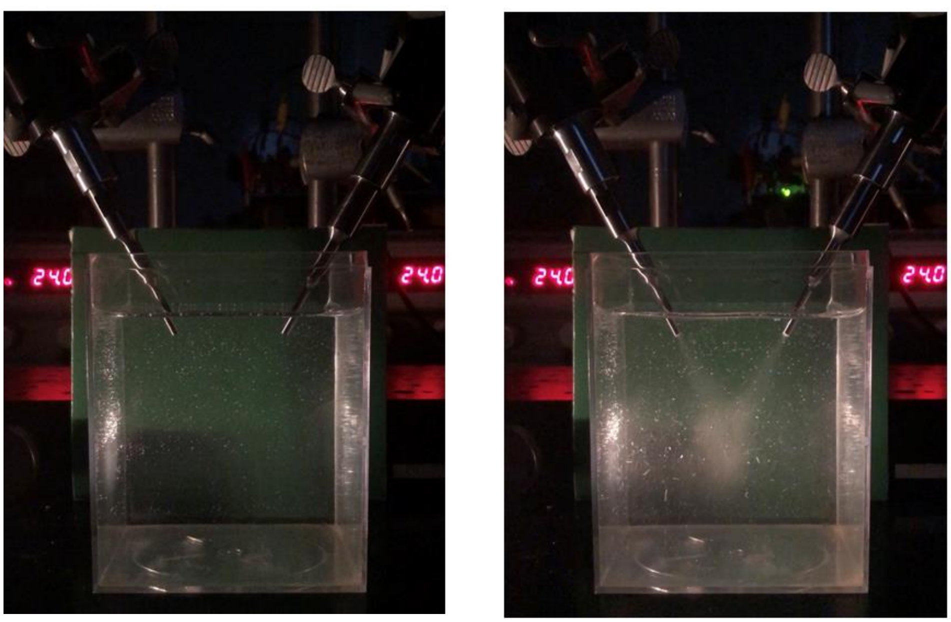

Figure 6. LHS: Ultrasound probes "off"; RHS: Ultrasonic probes "on" yields crossed turbulent streaming jets

4. HISTORICAL DISCUSSION

Lighthill's acoustic turbulent streaming jet theory has certainly evolved from earlier separate studies of streaming and turbulence. We will now outline the history behind Lighthill's predictions.

The following discoveries motivated Lighthill's theory: (a) Stuart[5] realized that a nonlinear equation of fluid motion is needed to describe streaming at high Reynolds number. (b) Reichardt's[6] turbulent jet flow measurements agree with Schlicting's[7] theory of turbulent jet flow from a conventional orifice, provided the fluid viscosity is replaced by a so-called eddy viscosity from turbulent mixing. (c) Squire[4] solved the nonlinear laminar jet flow problem exactly.

Lighthill realized the importance of (a,b,c) and coined the term RNW streaming for extremely low power, low Reynolds number applications, but recognized the merit of their contributions to the field. However, using "Stuart streaming" - requiring nonlinear convective acceleration terms - mathematically predicts the behavior of an ultrasonic turbulent streaming jet for acoustic power > 1 micro Watt.

i.e. Sound with large intensity – even at low frequencies can generate ultrasonic streaming that behaves like a turbulent jet flow – thanks to Lighthill's Acoustic Streaming Theory which predicts the flow behavior.

5. CONCLUSION

A turbulent ultrasonic streaming jet flow was successfully observed using a 40 kHz 1/8 inch diameter (3 mm) stepped horn probe. Further, the interaction of two crossed turbulent streaming jets was demonstrated. The interaction exhibited both a "forward" and "backward" flow field along the line segment bisecting the axes of each jet. The cavitation bubbles generated in the water due to the high pressure acoustic pressure fields allowed one to visualize the complex interaction of the jets. We also observed that the entrainment of each jet affected the other generating a complex large scale nonlinear turbulent interaction. In the future we plan to elaborate on this experiment by making PIV measurements and altering the viscosity (to increase sound absorption) by adding various amount of glycerol to the water.

ACKNOWLEDGMENTS

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