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W. K. Kramer

R. Grosskreutz

A. Dinkelacker

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ULTRASONIC STUDY OF TURBULENT WATER FLOW

W. Krämer, R. Grosskreutz, A. Dinkelacker
Max-Planck-Institut für Strömungsforschung
Göttingen, Germany

ABSTRACT

The propagation of ultrasonic waves through turbulent water flow has been investigated experimentally. While passing the turbulent region the sound waves are modulated to some extent. The degree of modulation and the frequency spectra of the modulation are closely related to the properties of the flow. It seems to be possible to use this method for turbulence measurements in liquids, whereby the absence of a probe in the flow region and a possibility to differentiate between velocity and density fluctuations would be special advantages. A disadvantage can be the fact that information is collected on the whole sound path.

INTRODUCTION

Propagation of sound waves through the turbulent atmosphere was studied in 1916 by G. I. Taylor[1]. Since this time considerable work, both theoretical and experimental, has been done in the field of sound propagation through a turbulent medium (see, for example, ref. 2 to 5). Experimental work on the scattering of sound by turbulence in water has been reported by E. G. Richardson[6] and D. J. Dunn[7].

This paper reports an experimental investigation of the transmission of ultrasound through turbulent water flow. Such investigations are interesting in two respects. Firstly, interest centers on the disturbances of sound waves travelling through turbulent flow (for example, to a sonar-signal sent through the turbulent boundary layer of a ship). Secondly, it is often desired to get information about the turbulent behavior of a flow without disturbing the flow with probes. The latter aspect was the principal aim of this investigation. It was thought that this information could be obtained from the modulation which sound waves show after traversing a turbulent flow.

EXPERIMENTAL ARRANGEMENT

A schematic diagram of the experimental arrangement is shown in Fig. 1. The turbulent mixing region of a free submerged water jet was used as the turbulent flow. It was generated by a rectangular nozzle with an orifice of 3 mm x 30 mm. A sound wave, transmitted and detected by quartz transducers, traversed the jet. The longer side of the nozzle was perpendicular to the direction of the sound beam. The frequency of the sound wave was about 1.5 MHz corresponding to a sound wave length of about 1 mm. The sound beam diameter was of the order of 5 to 20 mm.

When a sound wave passes through turbulent flow, part of the sound energy is refracted. This is caused principally by vectorial addition of the local velocity of the fluid and the velocity of the sound wave. The quotient of the mean velocity fluctuation and the sound velocity, the so called "turbulence-Mach-number", governs the refraction. In contrast to comparable experiments in air, the turbulence-Mach-number in water is very low, and therefore the intensity decrease by turbulent scattering is very low. A measurable decrease was, in fact, never found in this experiment. On the other hand, the amplitude fluctuations of the sound are significant and can

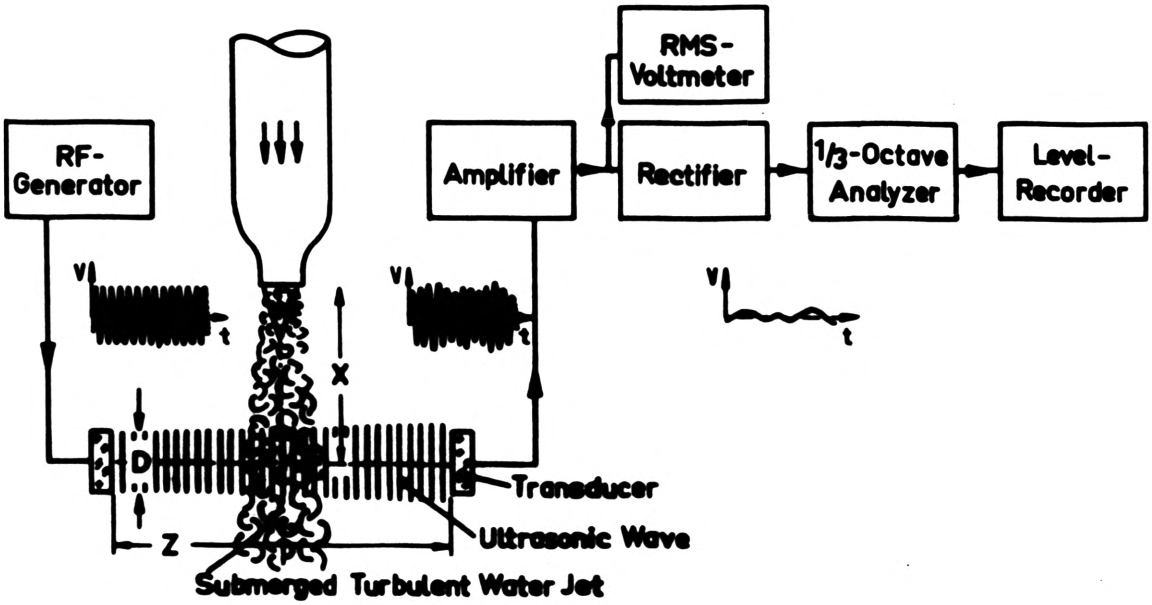

Fig. 1 Experimental arrangement

Typical experimental data:

Orifice of the nozzle	3 mm x 30 mm
Flow velocity U_k	1 m/s to 10 m/s
Sound frequency	1.5 MHz
Sound beam diameter D	5 mm to 20 mm
Distance between transducers z	50 mm to 1000 mm
Distance between nozzle and sound beam x	10 mm to 500 mm

be measured easily. After suitable amplification of the output signal of the receiving transducer, the signal is rectified and analyzed with respect to frequency.

EXPERIMENTAL RESULTS

Modulation Factor and Frequency Spectra

In Fig. 2 the modulation factor, m, is plotted versus the flow velocity, U_k, for the sketched geometrical arrangement. m is the quotient of the RMS voltage of the demodulated signal and the RMS voltage of the signal before demodulation. U_k is the mean flow velocity at the intersection of the axes of the sound beam and the water jet. As can be seen, the modulation factor is of the order of 1% and increases almost linearly with the flow velocity.

Additional information can be gained from the modulation spectra, as can be seen in Fig. 3a. In the upper part of the figure, there is plotted the modulation factor within 1/3 octave-bands versus the mean frequencies of the bands. Here the modulation factor is defined as the quotient of the RMS voltage in a 1/3-octave-band behind the demodulator and the RMS voltage of the modulated signal. Zero dB equals a modulation factor of one. One can see that the spectra for different flow velocities are similar and that they look in shape and frequency dependence very much like those obtained with other methods of turbulence measurement.

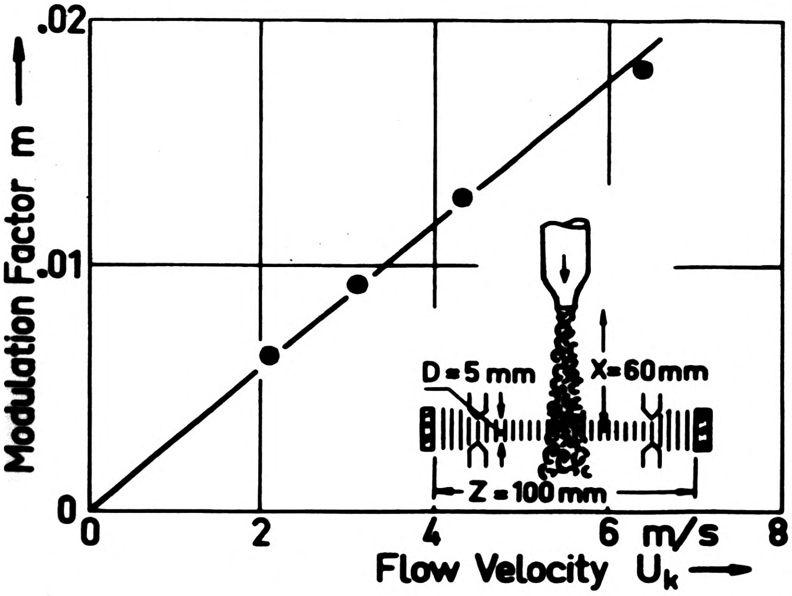

Fig. 2 Modulation factor m versus flow velocity U_k

The different curves may be brought to coincidence by a simple transformation, as seen in Fig. 3b. The transformation is done by dividing both abscissa and ordinate by the flow velocity U_k. The possibility of such a transformation is a strong indication that the modulation is really governed by velocity fluctuations which are proportional to U_k.

This does not necessarily mean that the plots shown are the real turbulence spectra. The slope of the curves, for example, depends somewhat on the adjustment of the transducers, and the decrease at higher frequencies is governed mainly by the finite diameter of the sound beam. Some results with sound beams of different diameter are shown in Fig. 4. The upper curve was obtained with a sound beam diameter of about 5 mm, and the lower one with a diameter of 18 mm. The flow velocity and the geometrical arrangement were the same in both cases. The decrease of the lower curve begins at lower frequencies, evidently due to a resolution effect. This is confirmed by comparison, in Fig. 5, of the spectra obtained by hot-film-technique and by sound scattering. The curves are brought to coincidence at 50 Hz. There is an astonishing correspondence for sufficiently low frequencies. At higher frequencies (higher wave numbers), larger signals are obtained by the hot-film, which has comparatively smaller dimensions.

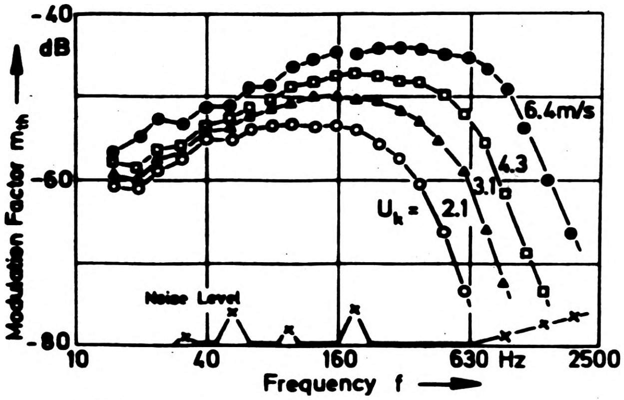

Fig. 3a Spectra of sound modulation

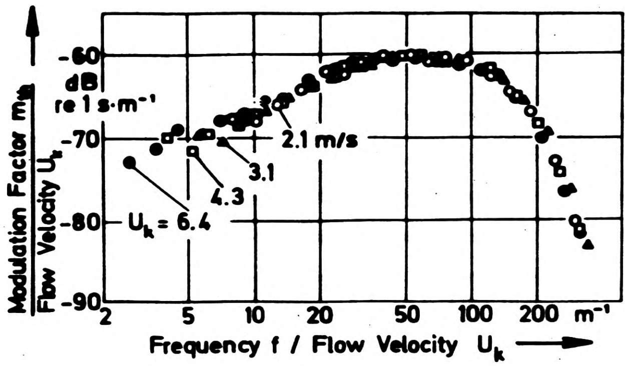

Fig. 3b Transformed spectra of sound modulation

Although the spectra do not show exactly the turbulent flow properties, one can still draw important conclusions about these properties from the

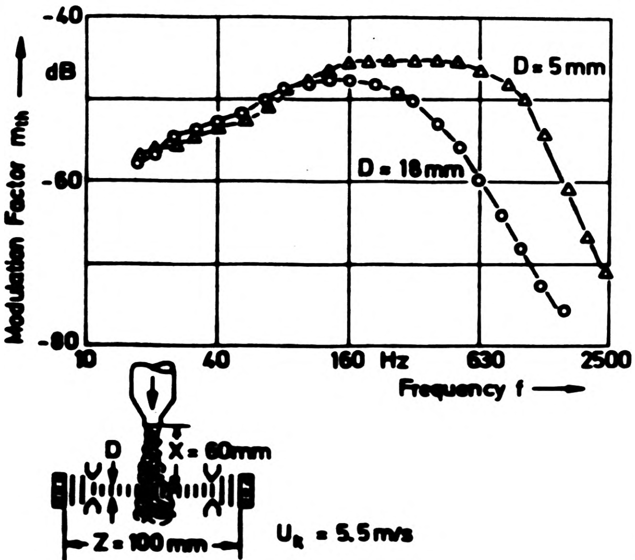

Fig. 4 Modulation spectra with different sound beam diameters

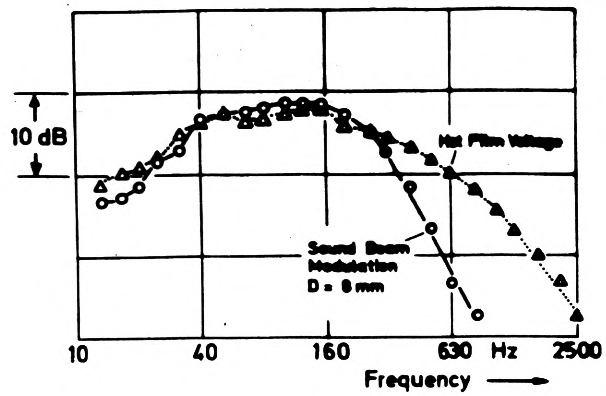

Fig. 5 Spectra of the sound modulation and a hot film signal; normalized for coincidence at 50 Hz

experiments in their present state. An example is given in Fig. 6. In this figure, modulation spectra are shown which were obtained at three different distances from the nozzle orifice. At 10 mm the intensity of the lower frequencies is small. There appear to be periodical parts in the spectrum at about 1 kHz, indicating periodical vortex separation at the nozzle. At greater distances the spectra are shifted to lower frequencies, indicating more large scale turbulence.

Separation of Thermal and Turbulent Scattering

Scattering of sound in turbulent flow can be caused in two different ways: (a) by turbulent velocity fluctuations and (b) by thermal inhomogenities. Usually both mechanisms are present simultaneously. Mechanism (a) is due to a vectorial superposition of flow velocity and sound velocity; mechanism (b) is due to a scalar change of local sound velocity. It is possible to differentiate between these two mechanisms with the help of sound waves travelling in the opposite direction. This can be done, for example, in an acoustic resonator system. In the arrangement used for this experiment, the transducers formed such a resonator. The quality of the resonator can be very high, depending on its geometrical dimensions. As will be shown later, the tuning of the resonator usually had no great influence upon the above reported results. With respect, however, to the separation of the two mechanisms of modulation, different tuning of the resonator can be used. Fig. 7 shows an example for such a measurement.At the upper right corner of the figure, a sketch is given of the resonance curve of the system. The voltage of the receiver is a nearly periodic function of the distance z between the transducers. The quality of the resonator is of the order of 1000. Tuning the resonator at maximum or at slope gives two different compositions of forward and backward travelling waves. At constant temperature, there is no difference between the spectra obtained with the resonator tuned in different ways (process (a) dominates). With 2°C temperature difference between jet and surrounding water a change in the tuning has a strong effect (process (b) dominates).

CONCLUSION

The modulation of sound waves transmitted through a turbulent water flow has been investigated. It seems to be possible to relate this modulation to the turbulent properties of the flow. Two principal advantages of the method are: (a) no probes disturb the flow, and (b) it should be possible to differentiate between velocity fluctuations and temperature or density inhomogenities. A disadvantage is that information is collected along the whole cylindrical beam path. It is hoped to overcome this disadvantage by correlating the signals of two crossed sound beams as was done with light beams by M. J. Fisher and F. R. Krause[8].

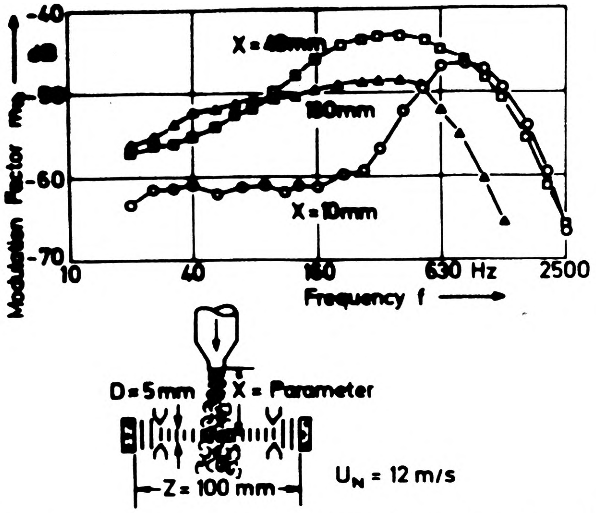

Fig. 6 Modulation spectra at different distances from the nozzle

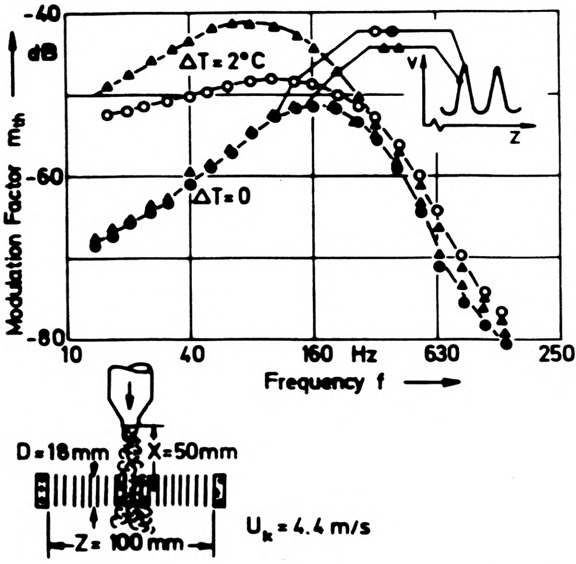

Fig. 7 Modulation spectra at different temperatures and different tunings of the acoustic resonator

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SYMBOLS

D	sound beam diameter
f	frequency, s^{-1}
U_k	flow velocity, m/s
m	modulation factor
x	distance between nozzle and sound beam, mm
z	distance between transducers, mm