EXPERIMENTAL SIMULATION OF THE SONIC BOOM AT THE LABORATORY SCALE

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ABSTRACT
The modelling of the sonic boom was carried out in the Sixties in order to estimate environmental impact of supersonic aircrafts. However for several problems, there were no quantitative model and these studies were motivated anew by projects of industrial developments of a new generation of supersonic aircraft. In this context, an experimental set-up dedicated to the simulation of the sonic boom in the controlled environment of the laboratory was developed. Initially, this system was used to simulate on a laboratory scale the focusing of shock waves on caustics, phenomenon which occurs for instance during the acceleration of the plane from subsonic to supersonic speed. The propagation of shock waves in heterogeneous media is another situation for which the models are still relatively empirical. In particular two problems are currently studied and will be presented after the results on shock waves focusing. Firstly influence of the turbulence of the atmosphere which is generally associated with heterogeneities of size comparable with the wavelength and can generate deformations and folding of the wavefront. Secondly the clouds for which the wave is scattered by the water drops whose size is much lower than the wavelength. These experimental results will be compared to numerical simulation.

INTRODUCTION
The modelling of the sonic boom started in the Fifties with the appearance of supersonic aircrafts. Thereafter, the interaction of weak shock waves and their propagation through heterogeneous medium was also studied in the framework of medical applications like lithotripsy which was developed in the Eighties. Recently, these studies were stimulated again by new projects of supersonic aircraft either to replace the Concorde or a new generations of SuperSonic Business Jet. The feasibility of such a project will depend mainly on its environmental impact and in particular on the mitigation of the sonic boom. The estimate of the latter requires a fine modelling of the shock which contains the audible frequencies. This modelling was not yet satisfactory in several situations such as, for instance, the focusing of the sonic boom which occurs during flight manoeuvres like acceleration from subsonic speed to supersonic speed. The propagation of acoustical shock waves (weak shock) in heterogeneous mediums is another situation for which the models are still relatively empirical [1]. In particular two problems are identified: influence of the turbulence of the atmosphere which is generally associated to structures of size comparable with the wavelength and may generate wavefront folding and the clouds that induce a scattering by the water droplets whose size is much lower than the wavelength. For these various situations there exist generally several modelling based on different assumptions and experiments are required to validate these theories. Measurements of the sonic boom in real conditions are very expensive and not easily reproducible taking into account the variability introduced by the weather conditions which are
moreover never perfectly known. The flight parameters, speed and trajectory, are another concern [2,3]. From this statement, experiments at a reduced scale and performed in the controlled environment of the laboratory are a tempting alternative. The majority of these experiments were carried out in the air. One can quote shock wave produced by explosions, projectile like supersonic bullets, or shock tube. More recently the experiments were carried out using electrical discharge in air produced between two electrodes, i.e, sparks, to produce weak shock waves “N waves” with a good reproducibility [4]. One can note that it is also this technique which allowed the development of extracorporal lithotripsy in water. The spherical diverging shock wave can then be transformed into a plane wave by a paraboloid reflectors. Nevertheless a certain variability of the waveforms results from fluctuation on the location and the intensity of the electric arc. The repeatability and the wave amplitude may be improved when the plasma is produced by a focused laser [5]. However, the reduction of scale is obtained by using higher frequencies and this results in a relatively higher attenuation (dominated in the case of the scaled experiment by viscosity and not by molecular relaxation) and thus a rise time proportionally longer. The experimental system that we developed is different. Rather than a gas as propagation medium we used a liquid, water, whose intrinsic viscosity is definitely lower. Moreover for liquid, array of powerful acoustic sources, array of piezoelectric transducers, were developed for medical applications in the MHz frequency range. This technical developments provide the opportunity of generating waves with perfect repeatability and amplitude high enough to reach the shock length in a few tens of centimetre. An another attractive feature of an array of source is the possibility to carry out electronic focusing. Finally when these arrays of acoustic sources are connected to a multichannel electronics able to synthesize a set of arbitrary signals, one may impose a boundary conditions on a finite surface in order to generate an a priori prescribed wavefield pattern. The computation of the set of signals to synthesize this field has been achieved thanks to a technique previously developed for adaptive focusing through heterogeneous medium [6].

The first section of this article describe the experimental set-up developed for the study of acoustic shock waves. Next we present some of the experimental results obtained first on the focusing of shock waves on caustics occurring for curved wavefront, second on the interaction of shock waves with a heterogeneous medium and last we present preliminary results on scattering by small particles.

EXPERIMENT DESIGN AND APPARATUS

The experiments are carried out in a tank of 1.3×0.8×0.6m filled with water. The ultrasonic waves are emitted by an array of 256 piezoelectric antennas (IMASONIC, France). The transducers have a rectangular surface (11×5mm) and are distributed regularly on a plane surface in a following way: 32 columns by 8 rows. The 256 transducers are not independent but are coupled two by two : first and eighth rows, second and seventh... so that this array was optimized for wave patterns possessing an axis of symmetry. To drive this array of 128 independent acoustics sources an electronic made of 128 arbitrary linear generators is required (ELECTRONIC LECOEUR, France). To get shock wave high electric power is delivered by broadband amplifiers that can provide each one 50 W peak so that the total amount is 6.4 kW. This kind of system may generate acoustic plane wave with an acoustic overpressure of 0.5 MPa at the frequency of 1MHz. The duration is limited by the size of the digital memory : 8ko at 40MHz of sampling rate resulting in 0.2 s of total duration. The measurement of the pressure field is ensured by a membrane hydrophone (PRECISION ACOUSTICS, UK), calibrated between 1MHz to 30MHz with a sensitive area of 0.2mm. The signals received by the hydrophone are digitized by a numerical oscilloscope. The hydrophone can be moved in the tank with a three axis positioning facility remotely controlled and providing an accuracy better than 10μm. The multichannel electronics posses its own PC board that is used to remotely control the whole experiment : scanning of the field with step motors and storing of the digitized measurements. A photography of the whole set-up is displayed on Fig. 1.
To compute the 128 code used to excite each couple of piezo-electric transducer, the inverse filter technique developed initially for adaptive focusing in heterogeneous medium [6] has been adapted here to synthesize collimated beam with prescribed wavefield pattern (called objective)[7]. This prescribed field is defined on a grid (called the control point) scanned by the hydrophone.

This method of synthesis proceeds in three stage, see Fig. 2. First of all the operator of propagation which characterizes the medium and the geometry of the experiment is measured. This step consists in measuring the impulse response between each couple of transducer and point of control. The second stage consists to numerically inverse this operator and multiplied it
by the prescribed field to get the set of 128 codes. In the third and last stage, these 128 signals are used to drive the array of piezo-electric transducer so that the objective wavefield is synthesized and can be measured. Taking into account the limited band-width of the piezoelectric transducers the field generated is made of a wavepacket at the central frequency of the transducers. But if the amplitude is sufficiently high a shock wave will be formed after nonlinear steepening. The experiment was designed so that the shock length is 30 cm, i.e a quarter of the tank. The scaling of the experiment with the sonic boom is resumed on table 1. The measured rise time of the shock wave at a distance of two shock length is 20 ns but this figure merely results from the limited band-width of the hydrophone that measures only the first 40 harmonics. The wavelength of the fundamental harmonic is 1.5 mm (1 MHz) and hence the scale ratio between the laboratory experiment and the sonic boom is of 1:100 000.

Table I. Scale ratio between sonic boom and laboratory scale experiment

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Ultrasound in water</th>
<th>Sonic boom</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wavelength</td>
<td>1.5 mm</td>
<td>100 m</td>
</tr>
<tr>
<td>Wave amplitude</td>
<td>&lt; 0.5 MPa</td>
<td>150 Pa</td>
</tr>
<tr>
<td>Rise time</td>
<td>5-10 ns</td>
<td>1-10 ms</td>
</tr>
</tbody>
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EXPERIMENTAL RESULTS FOR SHOCK WAVE FOCUSING

This experimental set-up was first designed to achieve a comparison with a numerical modelling [8] of the focusing of shock wave on a fold caustics. This situation occurs during the acceleration from subsonic to supersonic speed. Such experiments have been performed, but with no real scaling to sonic boom and no quantitative comparisons with a reliable numerical model. Moreover, most of these experiments were performed for cusp rather than fold caustics. The objective wavefield pattern is here the Airy function and the control point is a line perpendicular to the caustic. For the fold caustics, a radius of curvature of 10 m is selected to scale with the sonic boom. This fold caustic correspond to the red line on Fig. 2.

Figure 3.-Quantitative comparison for shock wave focused on a fold caustics

The pressure measured during one period and scanned along a line perpendicular to the caustic is displayed in colour scale on Fig. 3. The top of the figure correspond to the shadow zone (bottom-left of Fig. 2) and the bottom of the figure display the incident shock on the left and the “reflected” shock on the right. Note that the folded wavefront has here a cusp shape. From these measurements some pressure waveform are extracted for several spatial location. On the right the comparison between measurements (black), nonlinear modelling (blue) and linear modelling in the vicinity of the caustic (red) is displayed. These comparison [7] emphasized the accuracy of the nonlinear modelling and the key rôle of non linearities around...
the caustic as was theoretically derived 40 years ago [9]. This experimental set-up may synthesize various kind of wavefront and a second validation was performed for the cusp caustics [10]. Again a very good agreement was found and this study demonstrated that for weak shock wave of large enough aperture nonlinear flattening of wavefront was not able to prevent focusing.

EXPERIMENTAL RESULTS FOR THE EFFECT OF HETEROGENEOUS MEDIUM

Another facility provided by this experimental set-up is the possibility to interpose an heterogeneous medium and study its effect on the shock wave. To simulate the turbulence of the atmosphere speed of sound and density fluctuations are produced by moulded silicone rubber or others gels. With this kind of set-up different size of heterogeneities can be studied and for each heterogeneities a full scan of the pressure field is achievable. The scale ratio is very good since with at 1:100000 an heterogeneities of 100-200 m typical of outer turbulence scale to 1-2 mm. This kind of deterministic and hence perfectly repeatable experiment provides a mean to perform quantitative comparison with models. However a limitation compared to turbulent jet used in air is that flows are completely left out. More detailed results may be found in a paper by Ganjehi et al in this meeting.

Figure 4.-Measurement of shock wave behind an array of acoustical lenses

An example of a pressure field scan behind an heterogeneous layer made of several hemi-cylinder of 1.5 mm of diameter periodically spaced is displayed on Fig. 4 in color scale top of the figure and two waveform are extracted at the bottom. On the left the field at the focus range is displayed and focusing is clearly visible at for instance X=2mm and 5mm whereas in between the wave front remains plane. At X=2mm (bottom left) the “U” shape characteristic of focusing confirms this behaviour and an increased rise time is get. On the right one may note the complicated interference pattern resulting from this array of small acoustical lenses.

EXPERIMENTAL RESULTS FOR THE EFFECT OF SMALL SCATTERERS

The heterogeneous medium of interest may be numerous small scatterers. Again experiment may be conducted by using a cell made of a PMMA cylinder closed at each extremity by a very thin mylar membrane that is transparent to acoustic wave in the frequency range of interest. This experimental set-up is currently used to perform experiment of the influence of the
scattering on the rise time and amplitude of the shock wave. An example is displayed of Fig. 5, where the pressure waveform measured in homogeneous medium (black), through a mixture of water-ethanol (green) and through a solution of nano silica particles dispersed in a mixture of water-ethanol (red). The steepening due to the higher nonlinear coefficient of the water-ethanol mixture and the attenuation due to scattering are clearly visible. A detailed modelling is under development, see Baudoin et al in this meeting.

CONCLUSIONS
An experiment simulating the sonic boom focusing at the laboratory scale in a water tank with an exact similitude has been performed. This experiment has been used to demonstrates quantitatively the key rôle of non lineairities around fold and cusp caustics when shocks are present. Inverse filtering algorithm combined with a large 256 piezo-electric array provides a very flexible experimental set-up. Experiment are currently achieved to identify the influence of heterogeneities on shocks wave. For heterogeneities whose size is bigger or comparable to the acoustic wavelength focusing may be observed along with increase of the rise time.

References:

Figure 5.-Quantitative comparison for shock wave focused on a fold caustics