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Sound characteristics of a pipe with dynamically rough boundary

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Observing the acoustic field in the pipe above a dynamically rough water surface can provide a better understanding of the hydraulic roughness patterns and the change in these patterns which are caused by the hydraulic turbulence interacting with pipe wall roughness. This work presents results from a novel experimental setup, which allows for simultaneous measurements of the acoustic field in the pipe and water surface behavior. The acoustic and hydraulic characteristics were studied under controlled laboratory conditions, where six hydraulic regimes were used with a rough pipe bed condition. The acoustic technique makes use of acoustic Gaussian pulse which is transmitted in air above the turbulent water in the pipe. The scattering of the pulses was recorded on four non-equidistantly spaced microphones. The results obtained for the six flow regimes demonstrate that the statistical properties of the acoustic field are linked to the statistical properties of the dynamically rough water surface. This study demonstrates that the cross-correlation function of the four microphone pairs and the frequency spectrum statistics can be used for the flow water level and surface waves airborne measure. Statistical analysis methodology for the above techniques is briefly described.

1 Introduction

The interaction between the bed topography of shallow water flows and water surface waves has been a subject of study and discussion over several years. The experimental work [1-4], which was undertaken in pipes, channels and rivers, suggested that water surface waves can be potentially used as an indicator of bed roughness and overall hydraulic conditions.

Methods of water wave measurements are already well established [5-6], and can be implemented in channels and rivers. For the majority of the pipes however, these methods are impractical. As the pipes are installed underground and the access is limited by the single inspection hole or two manholes at either side of the pipe.

This work presents an alternative airborne acoustic method, where the device can be easily installed in the pipe to measure the mean water flow level and surface wave statistics. The above parameters can be used to calculate pipe wall roughness or other hydraulic properties of the flow. The methodology makes use of the cross-correlation function and probability density function.

2 Experimental set up

The experiments were conducted in 20m long, 290mm internal diameter perspex pipe, inclined at 0.2%. The pipe had smooth joins sealed with rubber sockets from outside, which gave a pipe wall roughness of k_s – 0.01mm [7].

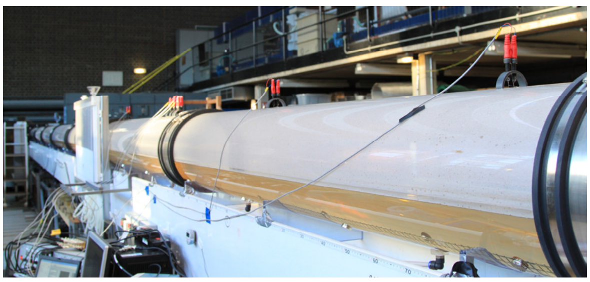

Figure 1: Perspex pipe arrangement.

The pipe was artificially roughened by the use of a square mesh with hexagonally arranged spheres. The 20m long, 200mm wide and 2mm high mesh was inserted into the base of the pipe, and was forced to fit the pipe curvature by the use of small tablet-like magnets. The mesh had squares of 20mm with 4mm wide boundary. The 25mm in diameter spheres were separated by 120mm along the whole length of the pipe, so that there was a repetitive pattern of one sphere in the center and two at the sides of the mesh. The following arrangement increased overall (distributed) pipe bed roughness to k_s – 4 mm and introduced objects which were observed to influence the water surface waves.

A set of seven resistance wave probes were used to capture the surface water waves statistics. The wave probes were located in the middle of the pipe between 9 and 16m. The exact wave probe locations were 10.43m, 11.56m, 11.62m, 11.68m, 11.71m, 12.81m, and 13.79m from the pipe inlet. This location was chosen such that the turbulent flow would be fully developed and uniform and without much influence of the pipe inlet and outlet.

A low-to-mid range speaker, Visaton TI100 [8] was located at 14.94m and oriented towards a set of microphones [9] located at 9.25m. The four microphones were non-equally spaced with 160mm, 320mm and 480mm separation. Before use, the microphones were carefully calibrated and their sensitivity matched. The distance between speaker and microphones was chosen such that the acoustic wave length was of similar length to separation.

To eliminate any acoustic reflections from the pipe end and outside incidental noise, sound absorbents were placed at both open ends of the pipe and the experiments were run in quiet lab conditions.

The wave probe and pulse reading were triggered to run simultaneously. For this purpose a LabView software was used. The acoustic and water level measurements for each pipe flow regime lasted 500s. The data from the wave probes was collected continuously at 90Hz and the Gaussian pulse of 315Hz was emitted via the speaker every 2s and recorded by four microphones in 20s packets and sampled at 22100Hz. The frequency spectrum of this pulse was below the frequency of the 1st cross-sectional mode (668 Hz). In total six water level regimes were used for the purpose of these experiments, where the experiments were conducted for water with flow (running water) and same mean level of water with no flow (still water). In all of the cases the background noise was recorded and it was established that signal to noise ratio is 1/10.

3 Conceptual model

The problem of identification of the water surface roughness by an acoustic pulse sensor is a case of describing the apparent rough boundary from the statistical mean of the emitted plane wave. The concept of this work was built up on the hypothesis that the statistical variation of the surface waves will fall in agreement with the statistical mean of the scattered pulse.

One of the models accounting for acoustic admittance [10] suggests that the geometrical properties and the statistical distribution of the rough surface can be described by the imaginary part of the effective acoustic admittance.

$$\beta(t) = -ik\frac{\pi N(t)a(t)^3}{3}(1-c)(1+c) \qquad (1.1)$$

$$c = \frac{\pi^2 a(t)^3}{4l(t)^3} \qquad (1.2)$$

Where N is the mean density of boils per unit area, *l* is the spacing between the boils and *a* is the boils radius.

This concept was developed for static ideal roughness shapes and its application to dynamic water roughness is questionable, however it suggests that the increase in roughness height results in the increase in acoustic admittance which controls the attenuation of the fundamental mode in the acoustic pressure field in the pipe.

A simple way to account for the finite imaginary part of the wall admittance (ψ_{00}) caused by the presence of the boundary roughness (*b*) is to use the expression for the fundamental mode in a pipe with the walls having a small, finite value of acoustic admittance (β), here *k* is the wave number and *r* is the radial distance from origin (Eq. 9.2.24 in [10]),

$$\psi_{00} = \beta\frac{kr}{4b} \qquad (2)$$

Another study [12] described the significance of the statistics in the pulse tail with regards to the surface roughness. It was concluded that the pulse tail contained the most valuable information on the surface roughness.

In our experiments the statistics of the water surface roughness will be calculated and analysed together with the statistics of the transmitted Gaussian pulse so that a link between the both characteristics can be established experimentally.

In these experiments signals recorded on each of the four microphones were filtered in the frequency range of 250 – 650 Hz using the Butterwort filter of 4th order to remove any noise and possible bias in the signal.

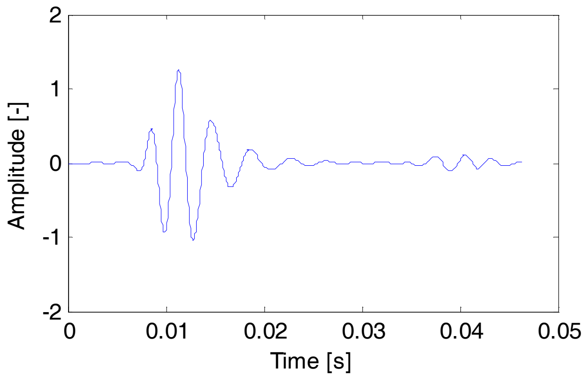

Figure 2: Filtered acoustic pulse for 86mm water flow.

Figure 2 presents an example of the filtered acoustic pulse which was recorded in the presence of 86mm water flow. It was believed that the presence of a dynamically rough surface results in multiple scattering effects which are mainly reflected in the variation in the pulse tail. Therefore a time window was used in the analysis to select the parts of the pulse which are affected by these multiple scattering phenomenon, which was found to correspond to the 7th extrema of the absolute value of the pulse, located in time window (t) of 0.0158-0.0178s of the pulse.

The mean absolute pressure (p) of the pulse is obtained, for all the recorded pulses (n) at all microphones (j).

$$\overline{p}_{j,n} = \frac{1}{T}\int_{t\,\min}^{t\,\max}(p_{j,n})dt \qquad (3)$$

Here, for the first technique a cross-correlation function (CCF) between four microphones pairs (m) will be used.

$$R_m(\tau) = \frac{1}{T}\int_{t\,\min}^{t\,\max}\overline{p}_m(\tau)\overline{p}_m(t+\tau)dt \qquad (4)$$

After obtaining six cross-correlation functions (R), for each of the flow conditions, the overall maximum value, the mean, the variance and the standard deviation of the six R maximums was considered in the analysis.

Second, for each of the water conditions (running and still) a frequency spectrum of recorded pulse was obtained using the fast Fourier transform (FFT) for microphone 1.

$$f_{n-1} = \sum_{n=0}^{N-1}\overline{p}_{1,n}e - i2\pi(n-1)\frac{n}{N} \qquad (5)$$

From the frequency spectrum (FS), for the maximum values at (302Hz) and two adjacent points (258Hz and 345Hz), the mean, variance, and the standard deviations were obtained.

The mentioned above parameters are believed to carry information on the change of the water surface data, and hence the roughness at an instant (particular) time moment.

4 Experimental results

4.1 Hydraulic data

The statistics of the free water surface are obtained from the resistance wave probes. The hydraulic data and statistics of the water level fluctuations are presented in Tables 1 for six water levels, each for running and still water conditions.

In the table 1, first column shows the test number and second column summarises the time-averaged water depth in the pipes cross-sectional center (h), measured by seven wave probes. The same water levels were used for still and running water conditions. The lower boundary of the flow was governed by the height of the pipe bed mesh with spheres, which was calculated from the pipe bottom in the middle of the cross-section. The highest water level (h) was determined by the speaker dimensions and by the dimensions of the anechoic terminations suspended from the top of the pipe and occupying approximately half of the pipe cross-section. Third column shows water level height (h) to pipe bed roughness height (k_s) ratio, where the maximum height of the roughness in the pipe center was considered. Columns four and five, as well as six and seven, demonstrate the time-averaged water surface waves amplitude (h_w) and these waves root mean square (W_{rms}), respectively for running and still flow conditions.

Table 1: Hydraulic statistics for running and still water.

			Running		Still	
Test	h	h/k_s	h_w	W_{rms}	h_w	W_{rms}
	mm	-	mm	mm	mm	mm
1	77	2.84	5.26	0.92	0.23	0.026
2	86	3.18	6.30	1.18	0.23	0.026
3	103	3.81	10.19	1.77	0.26	0.026
4	109	4.05	13.14	2.34	0.30	0.035
5	118	4.38	11.63	1.97	0.24	0.027
6	122	4.53	10.10	1.68	0.28	0.035

Figure 3 shows the wave height (h_w) as a function of water level (h) for running as still water conditions. For still water the fluctuations of water surface waves are equal to 0.26mm on average for all water levels (this occurs as in the still water experiments, the pipe end is blocked with the gate barrier and small leakage can occur). On the other hand, the fluctuations of surface waves heights increase with the increased water level in the case of running water. This happens up to the point when h/k_s ratio reached a value of 4 (h=109mm), further the waves do decrease with increasing water level. This phenomenon was observed by in the channels [4], where the roughness height to water level submergence ratio was established to have an effect on magnitude of surface waves. The yield point for channels was found to be equal to 8.

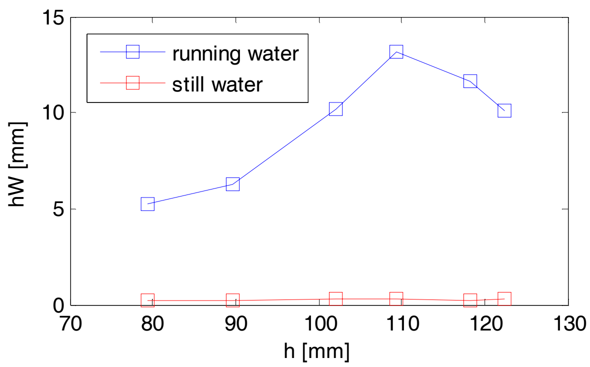

Figure 3: Time-averaged surface water waves amplitude as a function of time-averaged water level height.

Figure 4 demonstrates the surface water wave root mean square (W_{rms}) as a function of water height. The relation follows the same trend as in the Figure 3, and further examination shows that the increase in the wave amplitude height (h_w) results in the proportional linear increase of the wave roughness or the wave root mean square (W_{rms}).

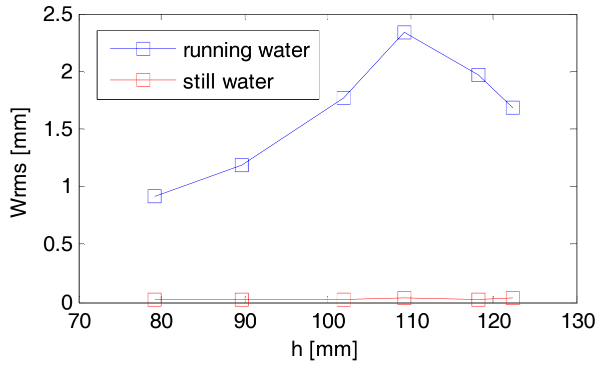

Figure 4: Root mean square of the water surface roughness as a function of time-averaged water level height.

4.2 Pulse CCF statistics

For the Gaussian pulse recorded on four microphones the cross-correlation function was calculated, where the statistical values of the function maximums were obtained.

Table 2 presents the data of the mean of the maximums of the correlation function (R_{max}) and the standard deviation of the maximums of the correlation function (σ_{Rmax}) for 7^{th} extrema of the running and still water. Other statistical parameters quoted in the Section 3 of this paper showed to have no relation with the water flow parameters as water depth or surface fluctuation.

Table 2: Cross-correlation function statistical data.

		Running		Still	
Test	h	R_{max}	σ_{Rmax}	R_{max}	σ_{Rmax}
	mm	-	- $(*10^{-5})$	-	- $(*10^{-5})$
1	77	0.9967	190	0.9969	100
2	86	0.9963	192	0.9962	49
3	103	0.9956	341	0.9960	90
4	109	0.9949	505	0.9950	93
5	118	0.9947	372	0.9944	62
6	122	0.9945	339	0.9941	95

Figure 5 demonstrates the mean of the maximums of the cross-correlation function as a function of water level. As expected both for the still and running water the lines follow similar linear trend, where with the increase of the water level the mean cross-correlation function decreases. A slight instability of the data for the running water may be related to the noise of falling water which is flowing from the pipe. Whereas in the case of the still water some noise from the outside may have affected the measurements.

Figure 6 demonstrates the relation of the standard deviation of the maximums of the correlation function (σ_{Rmax}) with the surface waves amplitude (h_w). The relation is close to exponential and both the data for the still and running water conditions are in good agreement. The parameter of σ_{Rmax} proves to be strongly affected by the scattering from the stationary or dynamic surface roughness. Evidently, with the presence of running water, for tests 3 and 6 when the h was different but h_w similar, the σ_{Rmax} values were similar as well. The parameter of σ_{Rmax} seems to be not affected by the mean water level in the pipe, i.e. the change in the pipes air cross-sectional area.

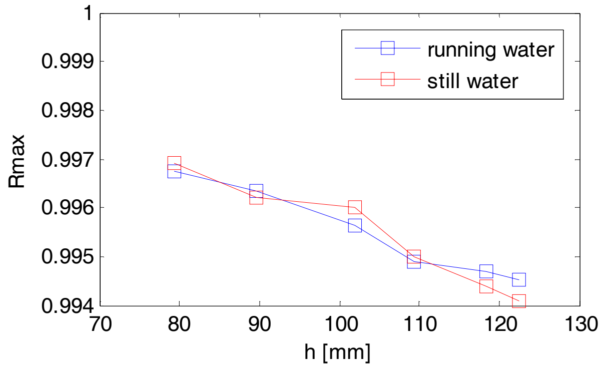

Figure 5: Mean of the six maximums of the CCF as a function of water level.

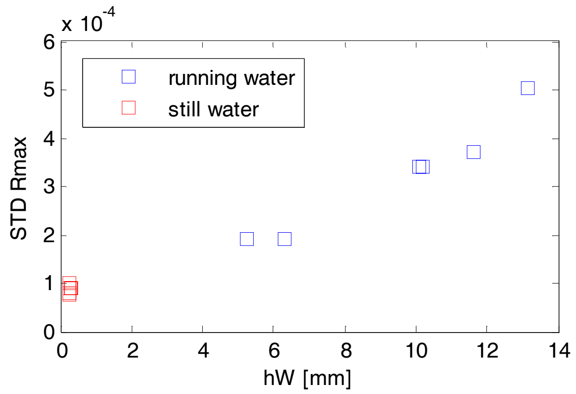

Figure 6: Standard deviation of the six maximums of the CCF as a function of surface water waves amplitude.

4.3 Pulse FS statistics

The statistics of the frequency spectrum (FS) were obtained for the maximal points at 302Hz and two adjacent ones at 258Hz and 345Hz for first microphone. The following analysis identified that the mean of the peak next after the maximum of the frequency spectrum (occurring at 345Hz) and the standard deviation of the maximum peak of the frequency spectrum (occurring at 302Hz) are the most valuable parameters in identification of the water level and surface wave amplitude respectively.

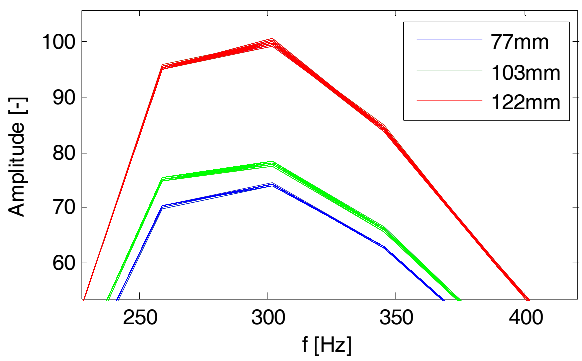

Figure 6: Frequency spectrum maximal points for three flow water levels.

Table 3 shows the values of the mean frequency spectrum at 345Hz (f_{345}) in columns three and five for the running and still water respectively. Also, the table presents the standard deviation of the frequency spectrum at 302Hz (σ_{f302}) for the running and still water in columns four and six respectively.

Table 3: Frequency spectrum statistical data.

		Running		Still	
Test	h	f_{345}	σ_{f302}	f_{345}	σ_{f302}
	mm	-	-	-	-
1	77	62.92	0.079	63.44	0.0389
2	86	65.31	0.102	65.94	0.0387
3	103	66.12	0.223	65.28	0.0325
4	109	69.28	0.298	67.57	0.0293
5	118	71.79	0.261	73.72	0.0363
6	122	84.22	0.231	86.64	0.0359

Figure 7 presents a close to exponent relation between the f_{345} and the water level (h), where the data regardless of the surface fluctuations is in excellent agreement for the pipe with running and still water. This function could be a result of a decreasing pipes air cross-section with an increase in the overall water level.

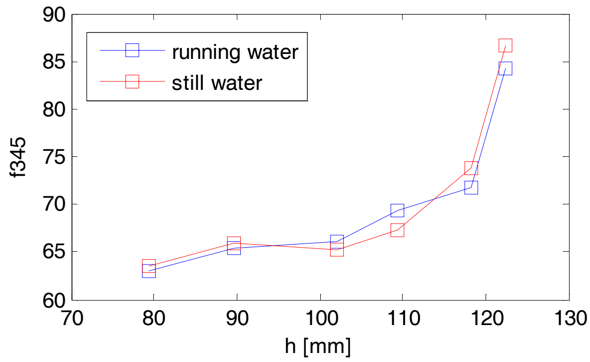

Figure 7: Mean of frequency spectrum values at 345Hz as a function of time-averaged water level height.

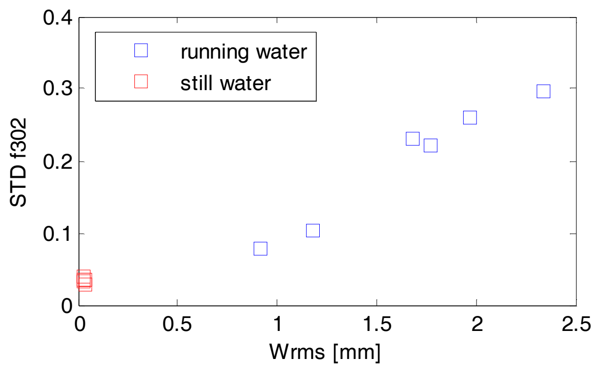

Figure 8: Standard deviation of the probability density function as a function of water surface waves RMS.

Figure 8 supports the theory of the sound pressure scattering due to the hard surface, either static or dynamic, and demonstrates a clear close to exponential relation between the σ_{f302} and the wave amplitude W_{rms}. The same parameter of σ_{f302} relates well with the wave amplitude, as it was found that W_{rms} is linearly related to h_w.

5 Conclusions

This work presents the statistical fluctuations of the free water surface waves in the circular pipe which were related to the statistical analysis of the transmitted Gaussian pulse. The work was carried out in the laboratory conditions where a circular plastic pipe was adopted for the purpose of the experiments. Seven resistance wave probes were installed in the pipe which recorded the water flow and surface statistics. A speaker and an array of four microphones were located in the middle of the pipe separated by some distance. The experiments were conducted over one rough bed for six water levels under running (with flow) and still (no flow) pipe conditions.

From the hydraulic data two major foundings can be extracted. First, the pipe at the current set up demonstrated a yield submergence ration (h/k_s) of 4. Before this value the effect of pipe bed roughness increases with the increasing water level and hence the velocity, and after this value, the effect decreases with the increase in water level. Second, the relation between the water surface wave amplitude (h_w) and the waves fluctuation root mean square (W_{rms}), are linearly proportional.

For the analysis of the recorded pulse two concepts were applied. First, a cross-correlation technique (CCF) between four microphones was used where further the statistical data of the maximum values of correlation function were obtained. Second, a frequency spectrum (FS) statistics for the data of 302Hz and 345Hz for one microphone was obtained.

The mean of the maximum values of the cross-correlation function between four microphones of 7^{th} extrema of the absolute pulse value (R_{max}) was found to relate linearly to the time averaged water level height in the pipe (h). However, even better ability to predict water level in the pipe was found via mean frequency spectrum values at 345Hz. This relation shows good agreement between running and still water data.

Furthermore, both the standard deviation of the cross-correlation function between four microphones of 7^{th} extrema of the absolute pulse value (σ_{Rmax}) and the standard deviation of the frequency spectrum values at 302Hz from first microphone (σ_{f302}), gave a remarkable relation with the time-averaged water surface wave amplitude (h_w) and wave root mean square (W_{rms}).

Moreover, rather than just relating the acoustic pulse pressure statistics to the water surface data, the data can be directly linked to the pipe flow parameters as the flow velocity and hydraulic roughness.

This study has presented two novel, airborne, non-intrusive acoustic methods of identifying pipe flow mean water level and the static or dynamic water flow surface roughness, either by the use of a single or an array of microphones.

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