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REPORT

Establishing a reference ultrasonic cleaning vessel:

Part 1: Supporting infrastructure and early measurements

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ABSTRACT

This document contains a description of the tasks completed within deliverable 4.5.1 "Establish a reference ultrasonic cleaning vessel" in the NMS Acoustics Programme 1998-2001. It includes the findings of a literature search, details of equipment specifications and performance, and the results of some initial hydrophone measurements carried out to assess the reproducibility of establishing a cavitating field using an ultrasonic cleaning bath.

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0 PROJECT DETAILS

This document reports on the tasks completed in support of deliverable 4.5.1 “Establish a reference ultrasonic cleaning vessel” in the NMS Acoustics Programme 1998-2001. The overall objective of the deliverable was to specify, procure, commission and test a reference high power/cavitating ultrasonic field source, along with its supporting infrastructure; and to characterise the field produced by the source so that the vessel may subsequently be used as a test bed. The tasks outlined in the original project plan are as follows:

Procure vessel, install and commission

a) Complete literature survey on environmental factors affecting ultrasonic cleaning
b) Produce specification for water management system and environmental enclosure, and procure both
c) Complete required modifications to drive unit of procured bath
d) Complete acoustic and non-acoustic tests to reproduce environmental conditions
e) Produce internal report

Develop PC control for scanning and data acquisition

f) Produce user and functional specification for positioning rig and put out to tender
g) Produce user and functional spec for PC control system and data acquisition
h) Install positioning rig (and other) hardware
i) Procure necessary PC hardware and software and install
j) Complete test programme of system motion and dummy signal acquisitions

Complete initial test using hydrophone as sensor

k) Complete tests of acoustic signal acquisition and post-processing
l) Complete reproducibility tests of cavitation field over limited range of output settings

The work reported here covers the period 1 October 1998 to 30 May 2000.

1 INTRODUCTION

1.1 OVERALL BACKGROUND

High power ultrasonic fields which can produce acoustic cavitation are found in a number of diverse application areas, which are illustrated in Figure 1.1. Broadly, applications identified in the figure can be divided into two main categories:

a) where cavitation is required by the process;

b) where cavitation is undesirable.

Generally, the further towards the top right of the figure that the application is displayed, the more likely it is to fall into the first category above.

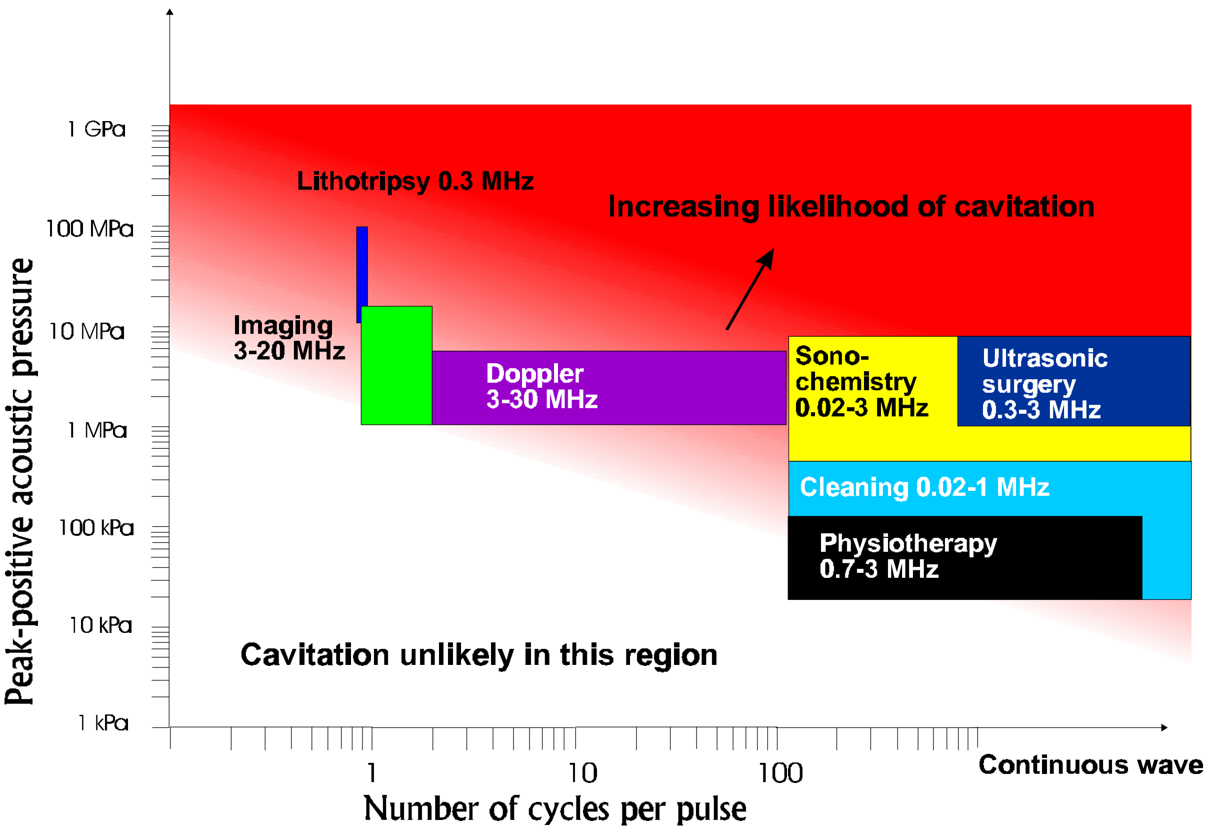

Figure 1.1: Applications of high power ultrasound

In recent years, commercial applications of high power ultrasound have shown consistent annual growths of between 10% and 30%. The importance of high power ultrasound was first highlighted in the UK in 1991 in a DTI-commissioned report, which identified it as being one of six 'hub technologies' whose implementation would lead to a cleaner environment (1).

1.2 ACOUSTIC CAVITATION

Generally, the mechanism by which high power ultrasonic fields bring about changes in a medium is acoustic cavitation, a phenomenon which can be described simply as the activity of small stabilised bubbles in a fluid subjected to an ultrasonic field. Many authors have classified cavitation in different ways (2, 3, 4, 5, 6), but perhaps the simplest approach is to subdivide acoustic cavitation into two types:

- non-inertial or stable cavitation;
- inertial or transient cavitation.

For a given medium and set of acoustic drive conditions, non-inertial cavitation is generally accepted as occurring 'first' at lower acoustic driving pressures, and qualitatively, consists of relatively stable, nonlinear bubble oscillations. The oscillating bubbles themselves act as acoustic sources, generating signals at harmonic frequencies of the drive signal. Increasing the driving pressure applied to the medium may, under a certain set of conditions, produce inertial cavitation, which is the phenomenon utilised in many of the applications displayed in Figure 1.1. It is the extreme environmental conditions associated with inertial cavitation which produce the effects of physical cleaning, free-radical generation, sonoluminescence and jet formation (7). The transfer and concentration of acoustic into cavitation energy can accelerate chemical reactions, enhance industrial processes and deliver therapeutic effects in medicine.

1.3 PROJECT BACKGROUND

In general, measurement methods for high power fields are needed for reasons of safety, for example in monitoring output levels of ultrasonic lithotripters in medicine, and also for device and process monitoring, for example in ultrasonic cleaning and sonochemistry.

Standard techniques have been established for the measurement of lower power ultrasound fields, centred on the medical field (8, 9, 10, 11). Indeed, declaration of the acoustic output levels of medical ultrasonic equipment is now in itself a requirement (12). However, with the exception of standards describing characterisation techniques applicable to lithotripters (13), and to ultrasonic surgical devices (14) there are few well-documented, traceable measurement methods for high power ultrasonic fields (7). Thus, there is an explicit need for standardised measurement techniques suitable for measuring the parameters which characterise industrial high power ultrasound fields, using calibrated instrumentation. Knowledge of these parameters would increase understanding of processes and applications, leading to optimisation and improved use of technology.

The need for standardised measurement techniques applicable to industrial high power ultrasound fields was identified by the International Electrotechnical Commission (IEC), who in the 1970's co-ordinated a brief investigation into the use of a multi-element thermal probe for characterising ultrasonic cleaning baths (15, 16). Problems with the reproducibility of the output signal led to these devices not being recommended. In the 1980's, a further IEC document was published, which reviewed a range of test procedures for ultrasonic cleaners (17). These included tests related directly to cavitation, as well as to soil removal experiments which focused more on attempting to quantify the cleaning process. The conclusions indicated generally the difficulties of developing acoustic field characterisation techniques suitable for standardisation in the high power area, and recommended further basic and applied research to control the many variables involved.

Recently, the needs of a number of users of high power ultrasound fields were summarised in a study report (18). The majority of the users indicated a requirement for a means of determining the activity or energy attributable to the cavitation process, as a function of time and space. This is reflected not only in medical applications, driven by concerns over health and safety, but also in areas such as ultrasonic cleaning, where some regions in a typical bath will clean better than others, and in sonochemistry, where knowledge of reaction locality will almost certainly lead to users and manufacturers being able to address the issue of scale-up on a more informed level. Standard techniques would also provide results that would be comparable between different systems.

Thus, there exists a clear need for measurement techniques that provide quantitative information about cavitation activity in high power ultrasound fields.

1.4 PROJECT RATIONALE

1.4.1 General

The recommendations of the study report (18) focused on the need to initiate an experimental programme with a low-level start, to attempt to develop a better understanding of the cavitation process dynamics. This approach also incorporates the IEC recommendations of the need for basic research (17).

1.4.2 High power ultrasound source

An ultrasonic cleaning vessel was chosen as the source of high power ultrasound, the principal reasons for this being:

- the comparative lack of ‘violence’ of the cavitation activity (intensities of just a few W cm^{-2} are produced, as opposed to the hundreds of W cm^{-2} produced by sonochemistry sources – see Figure 1.1);
- the accessibility of such a device (i.e. readily available ‘off-the-shelf’);
- the industrial relevance (worldwide market estimated at £2 billion, and measurement / monitoring requirements driven by quality systems such as ISO 9000);
- the long-term aim to characterise the cleaning process.

1.4.3 Supporting infrastructure

Many authors have reported that the surrounding environment has a significant effect on the reproducibility of cavitation activity (2, 5, 7), and so a water management system and environmental enclosure have also been set up. By identifying and controlling many of the factors that affect cavitation, and being able to monitor the remainder, differences in cavitation activity may then reasonably be assumed to arise from variations in the cleaning vessel performance. The use of a computer-controlled positioning and data acquisition system allows the precise re-location of measurement sensors, and a rapid and reproducible means of characterising the acoustic field.

1.4.4 Measurement techniques

There are a large number of techniques that have been used to characterise high power ultrasound and cavitation fields (7, 19). During the study report, the data received from the questionnaire respondents was coupled to that found from a review of the scientific literature, and a list of measurement and monitoring techniques for such fields was produced. These were critically appraised using a scoring system, incorporating criteria such as fidelity, relevance to a given process, accuracy and reproducibility. The results from this appraisal process showed that passive acoustic detection methods appeared to score most highly. This finding was fed into the study report recommendations, and hence forms the basis of the measurement methods employed in the current project.

Based on these three main areas, the overall aim of this project is to establish a reference ultrasonic cleaning vessel – a vessel that has been characterised extensively using appropriate techniques, such that a degree of cavitation reproducibility may be achieved. The term ‘reference vessel’ should be understood as representing the ultrasonic cleaning vessel in combination with the sensor scanning capability, environmental control, and monitoring and characterisation infrastructure built around it.

2 LITERATURE REVIEW

2.1 INTRODUCTION

The aim of this review is to establish the factors that affect cavitation. The way in which these factors influence the cavitation process is examined, and the findings then feed into the specification of the requirements for environmental control and monitoring. Throughout, the discussion will reflect the need to establish a reference cavitating field.

2.2 BACKGROUND

As alluded to in Section 1, acoustic cavitation is produced by acoustic pressure fields which originate from transducers radiating into a medium. As the liquid is stretched beyond its tensile strength during the rarefaction phase of the acoustic pressure cycle, bubbles present in the medium may grow from microscopic nuclei, and can then collapse violently during the compression phase. This phenomenon generally occurs at a rate dictated by the frequency at which the transducers are driven. The point at which cavitation starts to occur is known as the cavitation threshold, and is reached when the acoustic pressure applied to the medium is sufficient to drop the pressure below its vapour pressure during the rarefaction phase.

2.2.1 Cavitation inception and tensile strength

Initiating cavitation within a pure homogeneous liquid can be thought of as ‘tearing’ the liquid apart. The cavity so formed would contain vapour from the liquid together with any dissolved gasses present in the liquid. Hence, cavitation would then only be initiated when the pressure amplitudes result in tensions in the liquid which are greater than the tensile strength of the liquid. The theoretical tensile strength of water at room temperature is in excess of 10^8 Pa. In practice however, it turns out that cavitation can occur for stresses of the order of 10^5 Pa. This suggests that tensile strength is often heavily dependent on inhomogeneities and contaminants present in the liquid, and in some cases on the container walls. For example, when a liquid is degassed, it will be able to withstand much greater tension than when it is not (20).

The cavitation threshold has been found to decrease with (21):

- increasing dissolved gas content and surface tension;
- increasing temperature;
- increasing number of solid contaminants;

and increase with:

- increasing hydrostatic pressure;
- increasing dissolved ion concentration;
- increasing acoustic frequency.

2.3 IMPORTANT PARAMETERS

Some of the factors that affect cavitation activity will be reviewed here. These include frequency, acoustic streaming, ultrasonic power, temperature and dissolved gas content.

2.3.1 Frequency

In water, cavitation activity will occur over a wide range of frequencies, typically between 5 kHz and 5 MHz, depending mainly on the applied acoustic pressure. In the literature relating to ultrasonic cleaning, the term “cavitation intensity” is often used to describe the violence of the bubble collapses combined with the total number of bubble events. This term is a qualitative one and can be thought of as the total acoustic intensity that results solely from cavitation activity in the medium. At constant acoustic pressure amplitude, the cavitation intensity will reduce with increasing frequency, whereas the number of cavities within the medium at the resonant frequency will increase (22). Hence, if the acoustic pressure generated by the transducers remains constant, the bubble size will decrease with frequency, resulting in a less violent implosion. Estimates at various ultrasonic frequencies have shown that the number of cavitation sites is proportional to frequency (23).

The ultrasonic frequency does not affect cavitation so much as it affects the maximum radius to which the cavities can grow. At 40 kHz, a typical ultrasonic cleaning frequency, the cavitation threshold is of the order of one atmosphere, whereas at 850 kHz, it is in excess of 100 atmospheres (21). However, other data indicate a threshold of around 10 atmospheres at this frequency (21), perhaps showing the sensitivity to experimental conditions as well as the criteria for determining the existence of cavitation.

2.3.2 Ultrasonic power

Cavitation intensity is directly linked to ultrasonic power. For ultrasonic cleaning applications, the ultrasonic power delivered to the cleaning tank must ideally be adequate to cavitate the entire volume of liquid. In industry, the unit of watts per gallon is sometimes used to quantify the amount of power that needs to be delivered to the tank to fulfil the above criterion (22). It should be noted that the figures for the power levels quoted in the literature are generally not easy to relate to the acoustic power radiated in the medium, since these usually refer to the electrical power input into the transducers. Since not all transducers will convert electrical power to acoustical power with the same efficiency, it is not possible to evaluate the acoustical power output from a simple knowledge of the electrical power input.

If power is increased substantially above the cavitation threshold, cavitation intensity tends to fall off: when an ultrasonic beam passes through a medium containing gas bubbles, it sets these into vibration and as a result, energy is lost from the beam. The resonant gas bubble is extremely effective in absorbing and scattering energy from a sound wave (23). Also, if bubbles agglomerate around the transducers, shielding effects can occur.

2.3.3 Temperature

Temperature is one of the most important parameters to be considered when seeking to control a cavitation field. Within the context of establishing a reference cavitating vessel, it is debatable whether or not maximum cavitation activity is required. It will however be necessary to monitor this parameter and determine a range of temperatures over which cavitation activity is not considerably affected. Many of the properties of the medium which affect cavitation intensity are related to temperature. Temperature will affect viscosity, solubility of gas in the medium, the diffusion rate of dissolved gases in the liquid and vapour pressure. In pure water, cavitation is ‘maximised’ around 70°C (23). For maximum cavitation conditions, the viscosity of a given liquid should be minimised as high viscosity will result in more energy losses in the medium (24). Viscous liquids will not respond fast enough to allow the formation of cavitation bubbles and violent implosion (22). In the case of most liquids, the viscosity is reduced as temperature increases.

Due to growing vapour pressure and decreasing surface tension, the equilibrium bubble radius increases with temperature. Although low vapour pressures will result in cavitation bubbles that implode with relatively greater force, fewer bubbles will be generated and there will be an increase in the cavitation threshold (24). High vapour pressure, on the other hand, will lower the cavitation threshold and increase the number of bubbles but will cause these to collapse with less intensity (24).

Temperature will also influence subharmonic effects. It has been shown that subharmonic threshold pressures are dependent on temperature as well as on equilibrium bubble radii. These thresholds increase as temperature and bubble radii decrease (25). Subharmonics tend to arise in non-linear systems and generally indicate that a system can behave in a chaotic way (26). Note that an increase in the acoustic pressure can also lead to the presence of subharmonics.

An increase in temperature of a liquid will increase its vapour pressure, thus facilitating the occurrence of vaporous cavitation. Here, the cavitation bubbles are filled with the vapour of the cavitating liquid. Once the foreign gases are expelled from the liquid, vaporous cavitation occurs as vapour bubbles are compressed and actually imploded by the pressure waves (27). This type of cavitation is the most effective for cleaning purposes. However, as the boiling temperature of the liquid is approached, cavitation intensity is reduced as the liquid starts to boil at the cavitation sites (22).

2.3.4 Dissolved gas content

Although a low dissolved gas content raises the threshold of cavitation (21), the cleaning liquid should contain as little dissolved gas as possible if maximum cavitation conditions are required (23). During the bubble growth phase of cavitation, rectified diffusion takes place, whereby gas dissolved in the liquid is released and prevents the bubble’s violent implosion. As temperature is increased, the dissolved gas content is reduced. The diffusion rate of dissolved gases in a liquid increases as a function of temperature, hence helping to minimise the dissolved gas content.

If reproducible cavitation conditions are required, it is clear that a means of quantifying the degree of degassing, deionisation and filtration must be utilised. Also, changing the water at regular time intervals will be necessary since its properties will change over time.

2.3.5 Solid bodies in medium

Generally speaking, free floating bubbles will originate either from seed nuclei stabilised by a skin of impurities or from gas pockets trapped within crevices in solid bodies contained in the liquid or the container walls when the medium is subjected to a variation in acoustic pressure. Tap water will contain between 0.5×10^5 and 10^5 of these small solid bodies (motes) per cm^3 (28). Although most of these can be removed through filtering, most filters will tend to remove motes which are above a specific size. Hence, if reproducible cavitation conditions are to be expected, one should ideally have a way of monitoring the amount of solid bodies present in the medium. Clearly, this can be a problem in practice. If tap water is used, its concentration of solid bodies can be expected to vary from one day to the next. Even after filtering, one may find that the amount of these bodies present in the medium will not be the same from one day to the next. Since cavitation activity is directly linked to the presence of solid bodies in the liquid (28), the reproducibility of cavitation activity is likely to be affected. However, given the large number of motes present, day-to-day variations may not in reality be that great.

2.4 OTHER CONSIDERATIONS

Some other factors which affect, or which are a consequence of cavitation activity are reported here.

2.4.1 Acoustic streaming

When the Navier-Stokes equations governing the flow in a liquid are solved, there exists a time-independent component of particle velocity in addition to an oscillating component (21). The momentum absorbed from the acoustic field manifests itself as a flow of the liquid in the direction of the sound field. This flow is known as acoustic streaming (29).

Schlichting streaming occurs in a viscous boundary layer in a sound field. This streaming produces vortices of a scale much smaller than the acoustic wave length. Velocity gradients are large and transport is enhanced due to this streaming (21).

Microstreaming occurs near bubbles of a compressible substance such as gas in the irradiated liquid. In this powerful type of streaming, the bubbles scatter sound waves and generate remarkably swift localised currents which can also contribute to cleaning. The currents are most pronounced near bubbles undergoing volume resonance and located along solid boundaries (30).

2.4.2 Cavitation erosion

It may not always be desirable to have maximum cavitation. Whilst low dissolved gas content increases the cavitation threshold pressure, it will also increase the potential damage resulting from cavitation erosion, since the cavities which then form collapse more violently in the absence of cushioning gas. It has been shown that damage may be minimised by increasing the gas content of the liquid (21). It has been suggested by Plesset (21) that liquid jets emanating from collapsing bubbles could potentially result in surface damage. Jet velocities of over 100 m s^{-1} have been theoretically predicted and experimentally measured (21). Although very high temperatures and pressures can result from the collapse of a cavity, it is thought that erosion is more likely to be caused by these jets. According to Noltingk and Neppiras (21), the violence of the cavity collapse as a function of pressure will reach a maximum value and then decrease: as the maximum value of the bubble radius increases with the driving pressure amplitude, so will the time required for collapse. In the work carried out by Niederdränk and Wiesland (25), in the case of a tank filled with tap water, the measured value of the centre bubble radius for a distribution of bubbles was found to be 17.8 μm at a frequency of 20 kHz, whereas it varied between 6 and 14 μm for water degassed to different degrees for the same temperature and driving pressure. Within the scope of this work, conditions must be such that erosion of the tank walls, transducers and sensor is minimised.

2.4.3 Aqueous cleaning solutions

Surfactants are generally used to lower the surface tension of the cleaning liquid hence giving it the ability to penetrate and lift soils. In terms of achieving optimum cavitation, surface tension should be moderate. A high surface tension will generate bubbles with less elasticity. These will collapse with more intensity. A too high level for this parameter will however tend to impede the formation of bubbles. Low surface tension allows larger values for the bubble radii to occur but also results in a lower cavitation intensity (24).

2.5 SUMMARY

It has been shown that many factors will affect cavitation activity within a medium, the most important of which are:

- frequency;
- acoustic power, or acoustic pressure;
- temperature;
- dissolved gas;
- particulate content.

In attempting to generate a reproducible cavitation field, it is desirable to control and monitor the following parameters:

- **Water quality/quantity.** Dissolved gas as well as particulate content and conductivity will significantly influence cavitation. It is therefore vital to be able to quantify the concentrations of these quantities before tests, and to monitor them at regular points during measurements. Use of a water management system will ensure that the water is degassed and deionised to the same level before tests are carried out. During tests, the quality of the water will change, hence the need to monitor temperature and dissolved oxygen content through the course of the measurements and determine margins for these quantities within which variation in cavitation activity is minimal. Other dissolved gasses will not be monitored. The volume of water which is used should also be quantified and the cleanliness of the tank should be monitored. Particulate content, on the other hand, is more difficult to quantify and settling on a certain level of water purity is going to be opted for.
- **Frequency.** The fundamental frequency at which the transducers are driven will need to be monitored.
- **Transducer drive level**. The output voltage from the signal generator will need to be quantified so as to ensure that a reproducible drive signal to the transducers is produced. Whilst the acoustic field which is produced will vary with water quality and quantity, tying down and monitoring the drive voltage gives a degree of confidence in the acoustic source.

Some of the important factors affecting cavitation are summarised in the table below (see Table 2.1).

Table 2.1: Important factors affecting cavitation.

Factors affecting cavitation	Effect on cavitation
Frequency	• cavitation occurs between 5 kHz and 5 MHz • cavitation reduces with increasing frequency (23) • number of sites increase proportionally with frequency (23)
Ultrasonic power	• cavitation intensity tends to increase with applied ultrasonic power (22) • cavitation intensity tends to fall off when applied ultrasonic power increases above threshold of cavitation (22)
Temperature	• cavitation is maximised around 70°C in pure water (22) • vaporous cavitation is facilitated as the temperature of the liquid is increased (22) • cavitation intensity is reduced as the liquid starts to boil at the cavitation sites (22)
Dissolved gas content	• a low dissolved gas content raises the threshold of cavitation (21) • low dissolved gas content is desirable for maximum cavitation conditions (23)
Surfactant	• lowers surface tension of water and allows larger bubbles to grow (24) • reduces cavitation intensity (24)

3 ULTRASONIC CLEANING VESSEL

3.1 BACKGROUND

Based on the findings described previously, a cleaning bath was selected as the source of high power ultrasound, to produce cavitation conditions. In choosing a suitable cleaning vessel, the following areas were considered:

Availability (is it relevant to what is being supplied in the industrial market place?)

Physical size (will it provide a cavitation field which is sufficiently variable in space to allow us to characterise the field fully; will it fit alongside the infrastructure?)

Frequency (industrial relevance, can we characterise it fully using existing sensors?)

Variable output (can we make measurements over a wide range of cavitation conditions, perhaps below the cavitation threshold?)

Reliability (does the manufacturer have an established track record, so that we can have confidence in the reproducibility and lifetime of the device?)

Previously, some limited measurements had been undertaken on an ultrasonic cleaning vessel produced by Branson Ultrasonics, and so the decision was made to choose a Branson device again. Branson produce a large range of devices, and so advice was taken on a typical representative vessel commonly used is small-medium scale industry.

The vessel chosen was a Branson 6465-126-12CB cleaning tank (Figure 3.1).

Figure 3.1: Branson Ultrasonics cleaning vessel

The vessel contains 12 transducers which are bonded to the bottom of the tank in a 4×3 array. The tank has internal dimensions of 356 mm × 229 mm × 305 mm, and the transducers are driven at a fundamental frequency of 40 kHz by a Branson Series 8000 B9040-12 generator. The nominal power rating of the bath is 1 kW. The drive signal is an amplitude-modulated square-wave: the frequency and magnitude of the amplitude modulation are 100 Hz and 100% respectively. This modulation enables any bubbles coming out of solution to rise to the surface of the water and escape during the 'off' time, and thus is an effective means of degassing the medium. The generator also has a 'frequency sweep' feature, used during cleaning to provide a more homogeneous acoustic field distribution, by destroying the coherence of any standing waves that may be set up. This feature was disabled during the initial phase of measurements.

3.2 MODIFICATIONS TO ULTRASONIC GENERATOR

In original form, the signal generator was only able to vary the output power level between 20% and 100% of the maximum output power. However, Branson manufacture an optional input/output (I/O) board which was purchased and installed, and a custom-designed interface box produced. This provides the following capabilities:

- ability to control the output power by using an 'off-set' voltage applied to the board, giving much greater flexibility over of drive levels, and extending the operating range to below the 20% level;
- ability to monitor a voltage value that corresponds linearly to the output power, enabling better reproducibility of drive conditions.

Initially, it was hoped that this would extend the capability of the facility to encompass acoustic pressure levels producing conditions below the cavitation threshold. However, it was found that the bath appears to 'stall' at low drive levels, suggesting that there may be some feedback circuitry in the drive electronics that does not allow the bath to run in a sub-cavitation state. This will be investigated further in the follow on project, 4.5.2.

4 SPECIFICATIONS FOR SUPPORTING INFRASTRUCTURE

This Section outlines the thinking behind the equipment infrastructure that supports the facility, and concludes with the specifications of the various parts of the facility.

4.1 WATER MANAGEMENT SYSTEM

The water management system is incorporated into the system to control the medium in which measurements are made. Thus, the main focus of the literature review was to uncover those parameters which can affect the likely reproducibility of cavitation activity. Where appropriate, the findings from the literature review have been used to formulate the specification for the water management system. In particular, filtration and degassing were considered important, with these parameters examined alongside the need for a cost-effective system that could produce high quality water at a suitable rate. In addition, the industrial relevance of the medium was also considered, given that most cleaning baths utilise aqueous media.

Examination of the specifications of existing water preparation systems and the findings from the literature search led to the following specification for a new system:

- production rate around 25 l h^{-1}
- degassing capabilities to 1 ppm or better
- conductivity of < 1 µS cm^{-1}
- filter specification of 5 µm or better
- storage tank (allowing several fresh batches of water to be used per day)

The "*Option 30*" system from Elga was found to meet this specification, and an order placed. After installation and commissioning, the output specification of the system was as follows:

- production rate 30 l h^{-1}
- degassed water measured at 0.36 ppm
- conductivity of < 0.1 µS cm^{-1}
- filter specification rated at 5 µm
- storage tank of capacity 75 l

4.2 SCANNING RIG

4.2.1 General

To allow precise location of measurement sensors in the cleaning vessel, a positioning system was considered to be an important part of the supporting infrastructure. First considerations in specifying such a scanning rig were the space available, both in the current and future laboratory locations (31), and the size of the bath required to be characterised.

Typical sizes of commercially-available cleaning devices were studied: the largest tanks produced by most manufacturers had internal volumes of the order of 60-120 litres. For the largest Branson bath, the internal dimensions were 640 x 460 x 460 mm. Although the bath procured for this project falls into the medium sized category (internal dimensions

500 x 300 x 400 mm), it was agreed that it would be prudent to design and manufacture a scanning rig able to cope with larger devices: this leaves flexibility for future requirements.

4.2.2 Construction

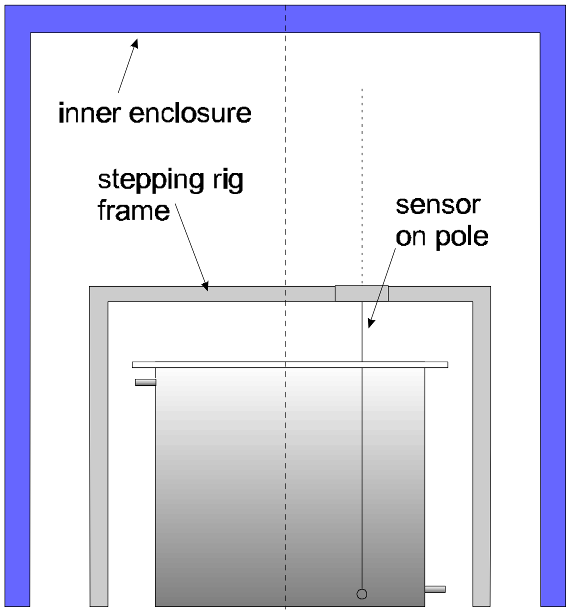

Figure 3.1: Schematic representation of bath, scanning rig and enclosure

Based on this overall size, a rig was specified and commissioned by Time and Precision Industries, Basingstoke, UK. This consists of a square section tubular construction frame with a single movable carriage, which forms the main support for the devices used to scan the cleaning bath field. Motor-controlled movement is provided in the longitudinal, transverse and vertical directions, with a positional resolution of 0.005 mm. The range over which the device may be positioned allows larger vessels to be characterised - longitudinal 650 mm, transverse 500 mm, vertical 500 mm. The whole system is controlled by a Windows PC, via an ISA interface.

The environment in the immediate vicinity of the cleaning vessel also needs to be controlled, in order that the effect of atmospheric contaminants can be minimised. Further, the audible emission is quite significant, and a means of limiting the extent of the noise pollution is desirable. The considerations of space described above are also important. From this, an enclosure was procured, whose specification was as follows:

- Of sufficient size to cover tank and scanning rig - approximate size 1.4 m wide, 1.4 m deep, 1.5 m high;
- Pair of clear opening doors at front, solid sides and back, clear opening top;
- Prime function is to shield tank from dust and other contaminants;
- Also to reduce audible noise emissions – panels are double glazed;
- Ports provided for water inlet and outlet to tank, and brush holes for cables;

Consideration was given to the most appropriate means of supporting the bath, the scanning rig and the enclosure: antivibrational feet are thus used on the mount which supports the cleaning bath, to minimise vibration transfer.

4.2.3 Software control

Bespoke software has been produced which fully integrates the positioning system and signal acquisition aspects of the facility. This is centred on a Delphi-based central .dll file, which employs simple scripts for carrying out the required measurements.

Acquired spectra and time-domain waveforms are stored in a hierarchical database (via GPIB transfer) for easy access. The database also includes ‘header’ information on parameters such as dissolved oxygen content, temperature, operator details, sensor details etc. The majority of signal processing is carried out after measurement runs have been performed using MATLAB, on which project staff have significant experience.

Currently, scanning capability is provided in 3 dimensions, by moving the sensor to a position, stopping, and acquiring a signal, usually with many averages to improve the signal-to-noise. However, an RMS meter can also be used on the system, and with appropriate filtering, it is envisaged that scanning may be carried out using a sensor without needing any averages, and so rapid spatial assessments may be made of bath output, perhaps as periodic reference checks. Producing the scripts for this will be a relatively straightforward task.

4.3 SUMMARY

Using the outputs from the literature survey, and considering the other system requirements, specifications have been generated and equipment procured that will provide the supporting infrastructure for the facility.

5 ACOUSTIC MEASUREMENTS

5.1 INTRODUCTION

The rationale for the project was to use acoustic emission techniques to characterise the cavitation signals produced by the cleaning vessel. Such techniques have been used by a number of authors (3, 7), and are based fundamentally on the use of devices that respond to the acoustic signals produced by oscillating and collapsing bubbles. A brief discussion of acoustic emission measurements is given here. Figure 5.1 shows a typical acoustic spectrum acquired in a 40 kHz high power ultrasound field, producing inertial cavitation.

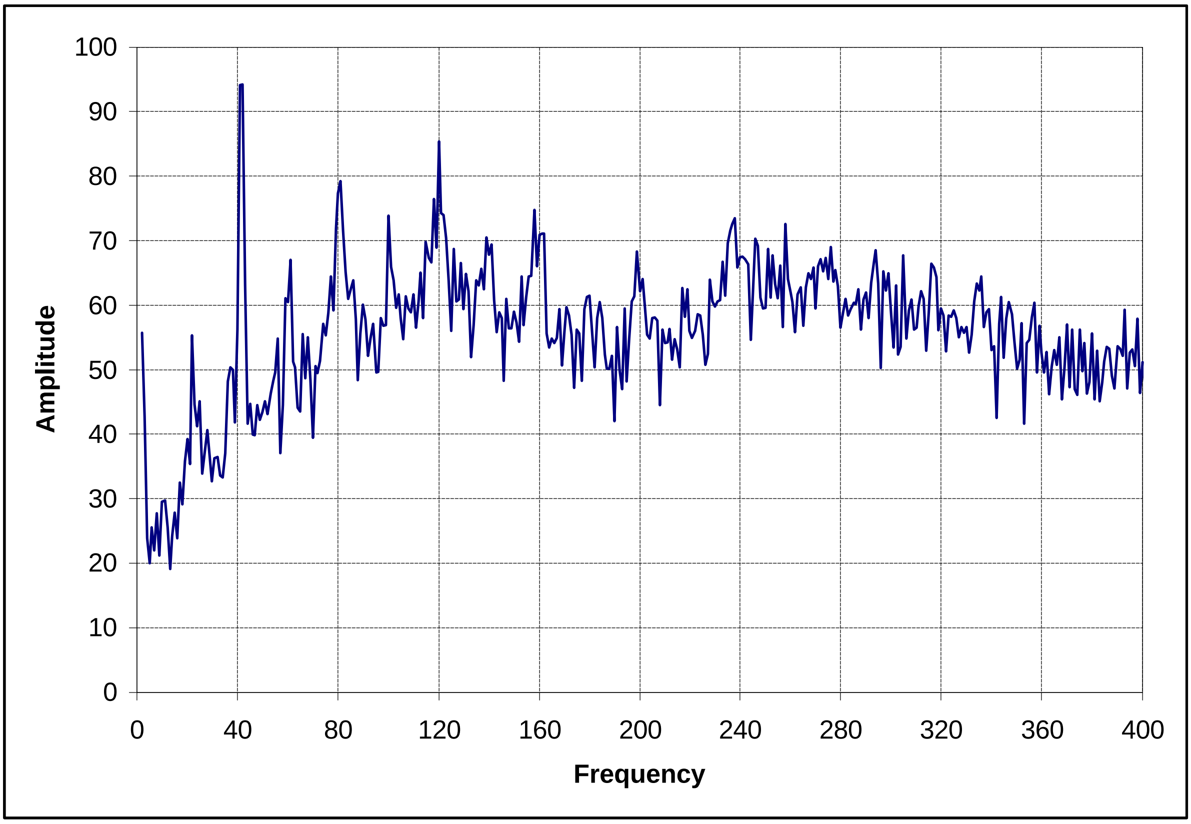

Figure 5.1: Typical acoustic spectrum produced by a cavitating bubble field

The figure shows a range of signals which are characteristic of cavitation activity:

- The fundamental frequency component at approximately 40 kHz – in the main, this is produced by the direct driving field, with further contributions from linear bubble oscillations (32);

- Harmonics of the fundamental, at integer multiple frequencies nf_0 (80 kHz, 120 kHz and so on) – these are the result of nonlinear bubble oscillations (33), and in some cases, acoustic signals produced by the transducers due to spurious signals in the drive circuitry;

- Subharmonics of the fundamental, f_0/n; here the 20 kHz signal can be seen – these are sometimes interpreted as indicators of the onset of inertial cavitation activity

(34), and can occur when a bubble of twice the resonant size is excited (35), or when a bubble takes two acoustic periods to reach critical radius before collapse (36);

- Ultraharmonics of the fundamental, mf_0/n, where m and n are integers; (60 kHz, 100 kHz and so on) – these are bubble events of a similar type to those producing subharmonics (37);

- Broadband signal – the ‘noise’ at all frequencies, produced by the shock waves emitted upon bubble collapse, and by collapsing bubbles of a wide range of sizes. This has been used as an indicator of inertial cavitation activity (38).

Note that hydrophone measurements of cavitating fields may also be sensitive to electrical signals produced by the transducers themselves: these will tend to be at the fundamental frequency, and at the integer harmonics, and will thus be superimposed on the ‘true’ acoustic spectrum. In the case of Figure 5.1, there appears to be structure in the noise envelope: this is due to the frequency response of the hydrophone used.

The cleaning vessel produces an acoustic environment which is rich in bubble activity: at any instant, a large number of bubble events will be occurring throughout the volume. Thus, any measurements made will in fact be a summation of cavitation events, and will also be influenced by reflections from the walls and the water surface, and electrical pick-up. Phenomena such as bubble shielding will further affect the data obtained. Care is thus needed to ensure that all possible aspects which may be controlled or monitored are known, maximising the possibility of gathering good-quality data.

5.2 GENERAL

This section describes a series of hydrophone measurements carried out in the cleaning tank to assess the day-to-day reproducibility of acquisitions of acoustic pressure spectra (incorporating all of the features listed above) as a function of hydrophone position and transducer drive conditions. Alongside the monitoring of environmental parameters, information from passive acoustic detection illustrates which acoustic quantity is suitable for assessing the cavitation activity in the tank and how reproducible the measurements of this quantity are. The work reported in this section includes some tests completed shortly after initial commissioning of the facility, and also some measurements completed later in the project, after aspects such as the scanning rig and bath modifications had been completed.

A series of preliminary tests were completed to assess the general reproducibility of the experimental conditions. Environmental factors and drive conditions which were monitored were as follows:

- percentage of maximum output electrical power from signal generator;
- water level;
- temperature;
- dissolved oxygen content;
- position of hydrophone in tank.

Initially, with the scanning rig not yet operational, the exact position of the hydrophone in the cleaning bath was difficult to quantify, with positional accuracy roughly ±1 mm. Similarly, the only means of monitoring the output electrical power from the signal generator was to rely on the LED display (1 LED corresponding to 5% of the maximum output power). Temperature and dissolved oxygen (DO_2) content were however monitored accurately from the outset by means of a calibrated thermometer (accuracy ± 0.1 °C) and a Hanna HI-9145 dissolved oxygen meter. This device measures the concentration of dissolved oxygen in parts per million (ppm), and has an accuracy of ± 1.5% f.s.d.

The water level in the tank is fairly easy to establish, simply by using a marker position on the inside of the tank whilst filling.

5.3 EXPERIMENTAL

5.3.1 HP Spectrum analyser

The system on which the spectra were measured was a Hewlett Packard 3589A Spectrum / Network Analyser. This analyser enables measurements of signals containing spectral components between 10 Hz and 150 MHz. Unless specified otherwise, 5 averages were used with a resolution bandwidth of 290 Hz for a Nyquist frequency of 400 Hz using a *swept spectrum* type measurement.

5.3.2 Hydrophone

B&K 8103 hydrophone. This type of hydrophone is designed for high-frequency underwater measurements (cavitation noise, shock waves, ultrasonic baths, etc.) and for use in very confined spaces. Specifications are as follows:

- Integral 6m low-noise cable with miniature plug
- Element size: 8 mm piezoelectric cylinder of 6.35 mm in diameter
- Charge sensitivity: Approximately 0.12 pC / Pa
- Frequency range: 0.1 Hz to 180 kHz (+ 3 dB, – 10 dB)
- Operating temperature range:
  - Short term: – 40 to + 120°C (– 40 to + 248°F)
  - Continuous: – 40 to + 80°C (– 40 to + 176°F)

5.3.3 Experimental protocol

Temperature was monitored every other measurement and the dissolved oxygen content every 4 measurements. Typically, after being degassed, the water will have a dissolved oxygen content of about 3.8 ppm and a temperature of 20°C at the beginning of a run. Due to the high power ultrasonic field in the cleaning bath, the temperature can sometimes increase by 8°C in just one hour, also causing an increase in the dissolved oxygen content of about 2 ppm. As mentioned in Section 2.3.3, this will affect cavitation activity, hence the need to change the water at regular intervals to ensure reproducible conditions. It was agreed that the temperature was not to exceed 28°C and the dissolved oxygen content not to exceed 6 ppm. Tests have revealed that the spectral content of acquired signals is not considerably affected by variations of these quantities within these ranges. By the end of each set of measurements (i.e. for 17 acquisitions, each corresponding to a single power setting), the above-mentioned limits are usually just met and it is necessary to change the water. Note that the higher the power setting, the quicker the rise in water temperature and DO_2 content.

5.4 MEASUREMENTS AT CENTRE OF TANK

5.4.1 Data acquisition with a B&K 8103 hydrophone

Four independent sets of measurements were carried out in which the acoustic signal determined at the centre of the tank was measured with a B&K 8103 hydrophone. Measurements were carried out for output electrical powers ranging between 20% and 100% of the maximum output electrical power from the signal generator in steps of 5%. Selected plots are shown in Figures 5.2-5.4.

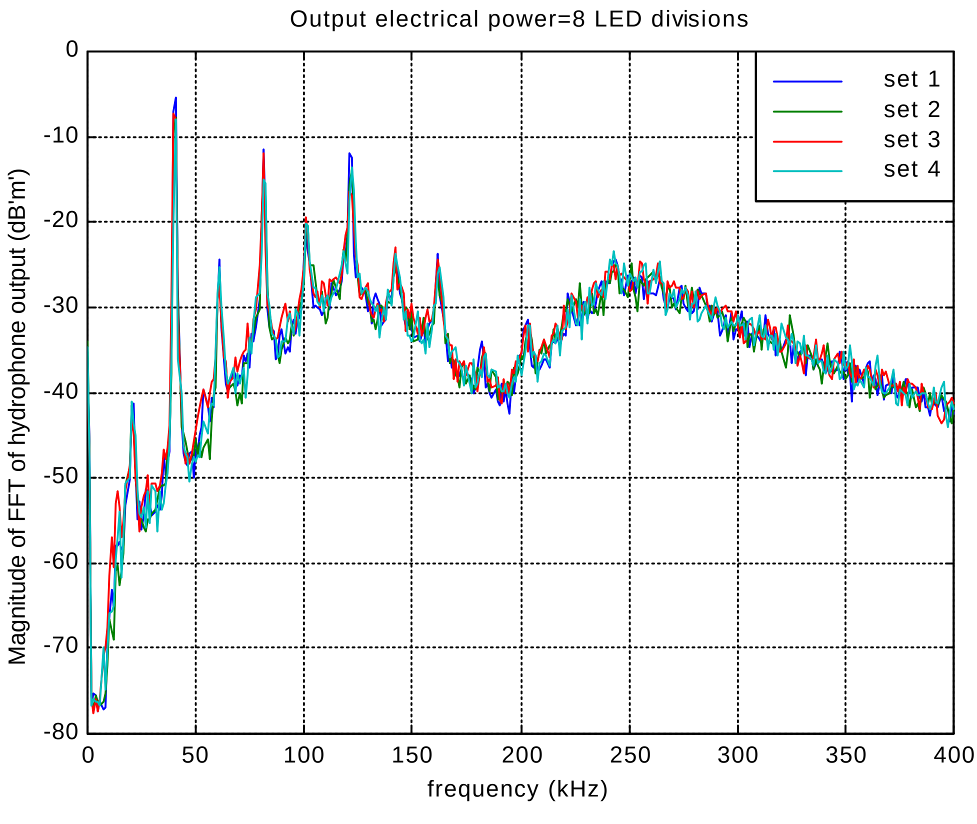

Figure 5.2: Hydrophone spectra at centre of tank for 4 sets of measurements. 40% of maximum output electrical power from generator

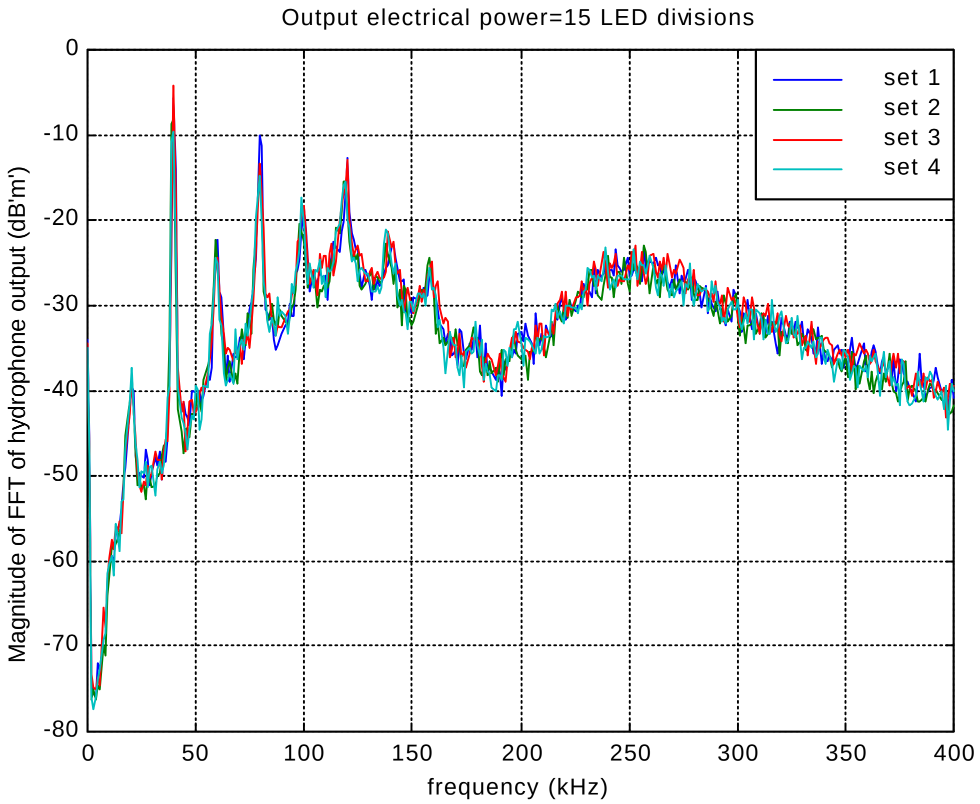

Figure 5.3: Hydrophone spectra at centre of tank for 4 sets of measurements. 75% of maximum output electrical power from generator

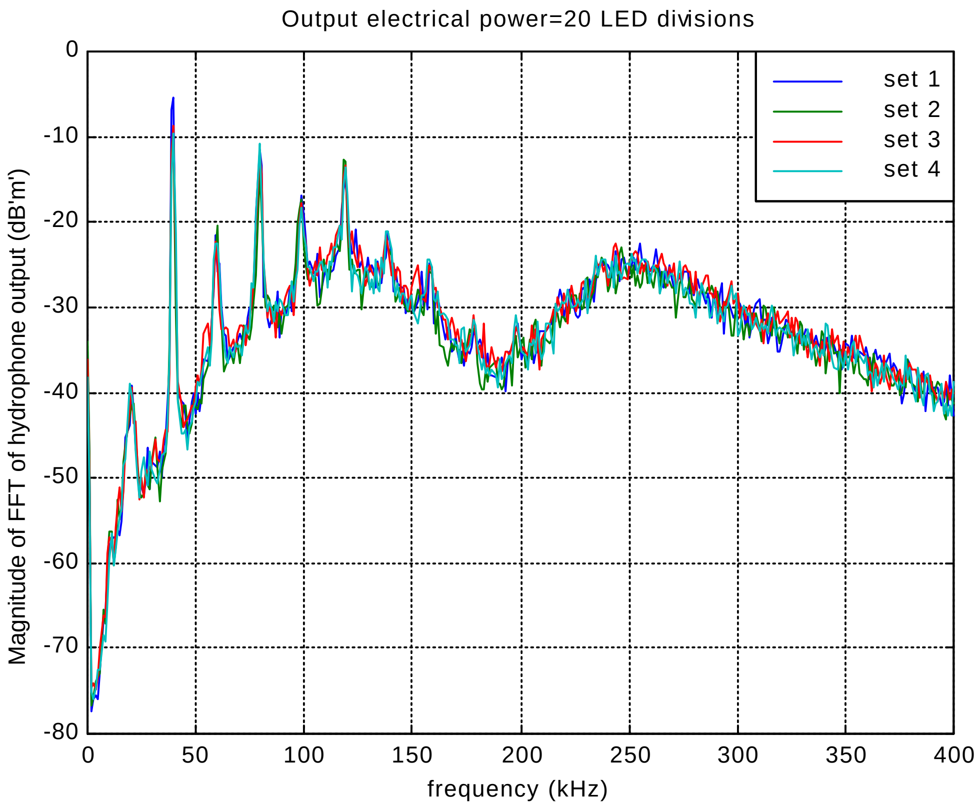

Figure 5.4: Hydrophone spectra at centre of tank for 4 sets of measurements. 100% of maximum output electrical power from generator

Figures 5.2-5.4 show that the received acoustic signal consists essentially of a broad-band noise envelope upon which harmonics of the fundamental drive frequency are superimposed. This confirms what has been mentioned in Section 5.1. The fundamental is at around 40 kHz, as expected. The first 4 to 5 harmonics are clearly visible. The presence of a subharmonic, occurring at half the frequency of the fundamental (20 kHz), together with ultraharmonics, which appear at integer multiples of the subharmonic, shows that the time-domain pressure signal has reached the point of the first bifurcation (period doubling) (26). As the electrical output power to the transducers is increased, it appears that some acoustic energy is transferred to the subharmonic, which is expected (see Section 2.3.3).

Note that the background levels do not appear to increase significantly when the output electrical power from the generator is greater than approximately 65% of the maximum output power (see Figure 5.5). This suggests that the system reaches a point where it is saturated and hence no longer behaves linearly.

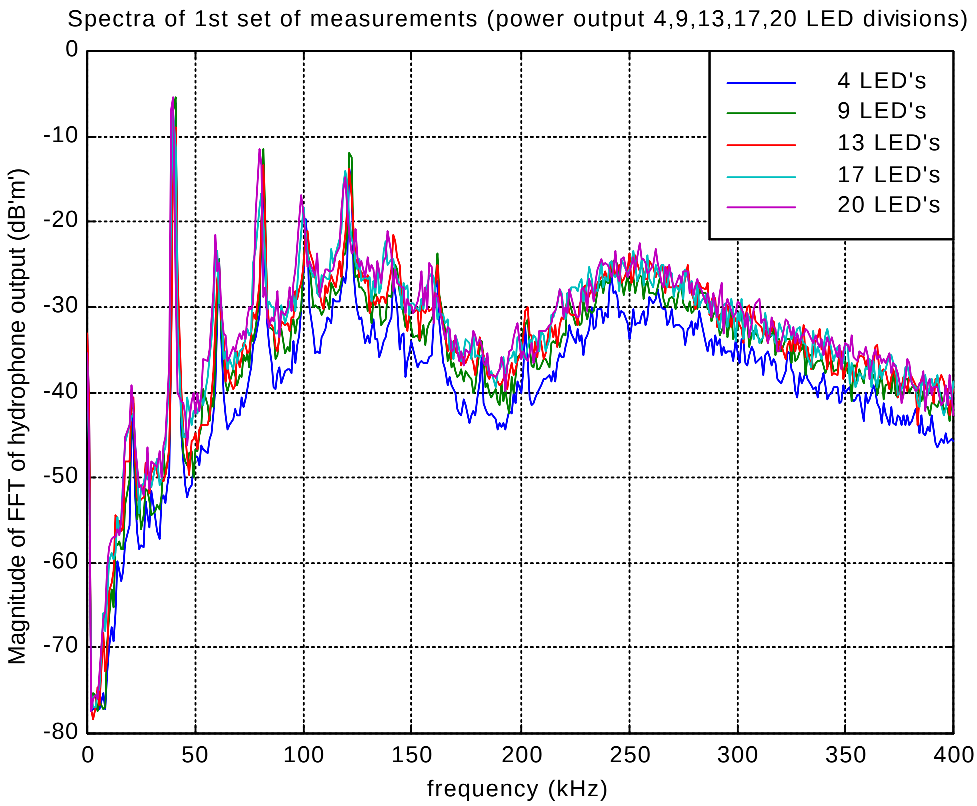

Figure 5.5: Hydrophone spectra at centre of tank for first set of measurements. 20%, 45%, 65%, 85% and 100% of maximum output electrical power from generator

The discussions in Section 5.1 suggests that the noise envelope is directly linked to bubble activity, whereas the harmonics are the result of both bubble activity and also acoustic signals produced by the transducers as a result of the square wave excitation of the bath. A simple test in which the hydrophone was placed outside the cleaning tank showed that only background noise was acquired when the ultrasound generator was on. This demonstrates that contributions from electrical pick-up are negligible. The subharmonics and ultraharmonics are more likely to be linked exclusively to bubble activity. In Figures 5.2 to 5.5, there is clearly some significant structure superimposed on the background noise. This is due largely to the response of the hydrophone (see Section 5.4.2.1).

There is some variation in the magnitude of the harmonics from one set of measurements to the next. Also, there are some small variations in the frequency value of the fundamental and harmonics for different runs. The variation in the frequencies of the harmonics is likely to be due to fluctuations which originate from the signal generator. It is likely that the number of bubble events will contribute to variations in harmonic amplitudes. It is however encouraging that there is little variation in the background levels from one run to the next at a given power setting. This perhaps tentatively suggests that the number of bubble events is relatively large and that a small variation in this number does not cause much change in the background level, hence indicating that the source of the water is reproducible. The amplitude modulation of the drive signal produced by the signal generator will further contribute to variations in the fundamental and harmonics in the spectra.

Generally, it is difficult to assess the overall results in terms of the magnitude of the harmonics and sub/ultra-harmonics: frequency resolution problems may further enhance the variation in amplitude and frequency. Further, it has been reported in the literature that acoustic signals of this type often originate from non-inertial cavitation activity, whereas the increase in the noise envelope has been suggested to originate from increases in inertial cavitation (32). As a cavitation monitoring means, it may be more appropriate to use the broadband noise envelope.

5.4.2 Signal processing

Once acquired, the spectra were processed in MATLAB. First, the spectra were corrected for the hydrophone response, which was obtained via a calibration. As the frequencies at which the calibration was performed did not all correspond to the frequencies of the points in the spectra, interpolation and extrapolation techniques had to be used. The corrected spectra are then squared and smoothed, and the peaks corresponding to the harmonics, subharmonics and ultraharmonics are removed. The energy contained in the 0-400 kHz frequency range of the spectrum is then derived by integrating the data between these frequencies.

5.4.2.1 Correction for hydrophone response

The spectra shown in Figures 5.2 to 5.5 were given in dBm units. They may be converted into volts through use of the following equation:

$$V = 10^{\frac{L}{20}}\sqrt{0.05}$$

where V is the voltage in volts and L is the output level from the spectrum analyser in dBm.

In Section 5.1, it was mentioned that there was some structure superimposed on the acquired voltage spectra resulting from the response of the hydrophone. The pressure spectrum may be obtained by dividing the voltage Fourier transform by the response of the hydrophone at each frequency. A fine-frequency free-field calibration for the latter has been produced between 10 kHz and 1 MHz at the following frequency steps:

- 1 kHz between 10 and 200 kHz;
- 2 kHz between 200 kHz and 300 kHz;
- 5 kHz between 300 kHz and 500 kHz;
- 10 kHz between 500 kHz and 1 MHz.

Only the magnitude data is available, which unfortunately makes it impossible to obtain the true acoustic waveform by means of an inverse Fourier transform. However, the spectrum may be corrected for, and the magnitude of the FFT of the acoustic signal in Pa Hz^{-1} obtained. A cubic spline polynomial interpolation routine was used to estimate the magnitude of the response of the hydrophone between 10 and 400 kHz in steps of 1 Hz, i.e. at the frequencies of the acquired spectrum (Figure 5.6). The data between 0 and 10 kHz was extrapolated in the same way.

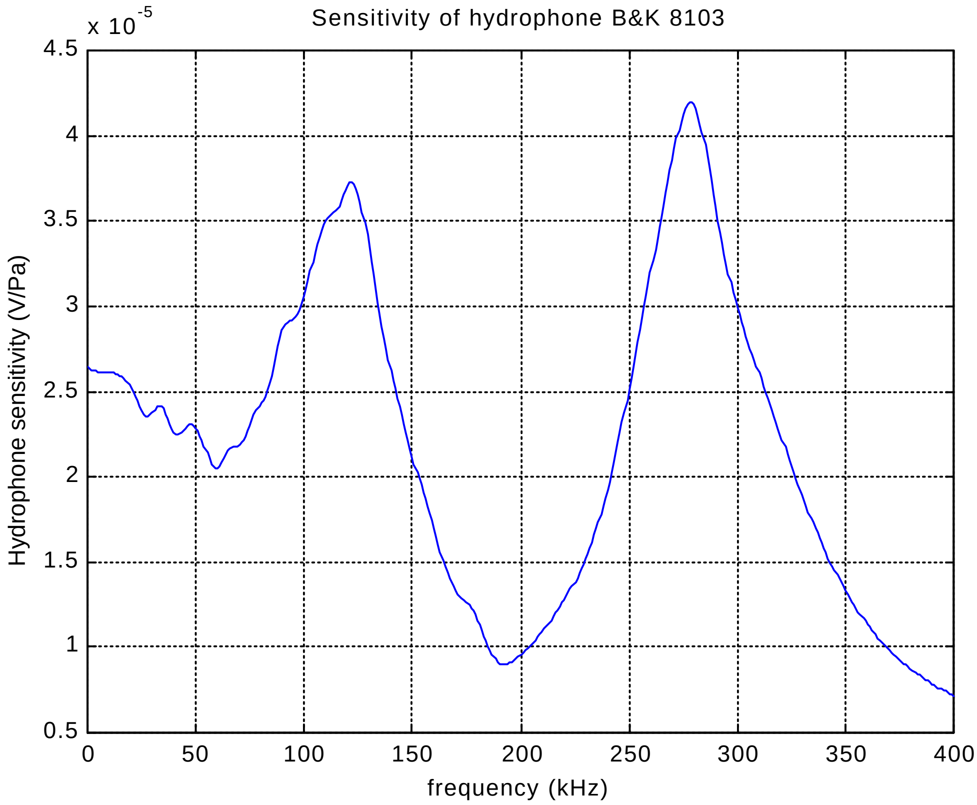

Figure 5.6: Hydrophone response obtained from fine-frequency calibration data.

The interpolated response exhibits 2 resonances, one around 120 kHz and another around 280 kHz. From the measured spectra shown in Figures 5.2 to 5.4, it can be seen that, although the first resonance seems to have been correctly represented, the other differs by about 30 kHz. A possible explanation is that the resonance frequencies of this particular hydrophone have a tendency to shift with a variation in temperature: the fine frequency calibration was produced between 18.4°C and 18.9°C whereas the measurements were done at temperatures between 20°C and 28°C. However, the measured spectra do not show such a radical shift throughout the course of the measurements and it appears that only the higher resonance is affected by this shift. It is likely that the conditions under which the hydrophone is operated differ significantly from those during the calibration and this is likely to have an effect on the way the hydrophone responds. In the cleaning tank, the conditions approach those of a diffuse field, and the hydrophone will receive sound from all angles of incidence. From the specifications of the B&K 8103 hydrophone (see Section 5.3.2), it is known that the latter will not behave as an omnidirectional receiver at all frequencies. The response of the hydrophone is a function of frequency and angle of incidence and the net output voltage of the hydrophone at a given frequency will differ from that obtained in a free-field situation (i.e. the environment in which the hydrophone was calibrated). At this stage, it is difficult to provide a quantitative explanation of this effect and more investigation is needed.

The spectra that would result from the deconvolved voltage waveforms can then be obtained by dividing the measured voltage spectra by the magnitude of the hydrophone response at each frequency (see Figures 5.7 to 5.9).

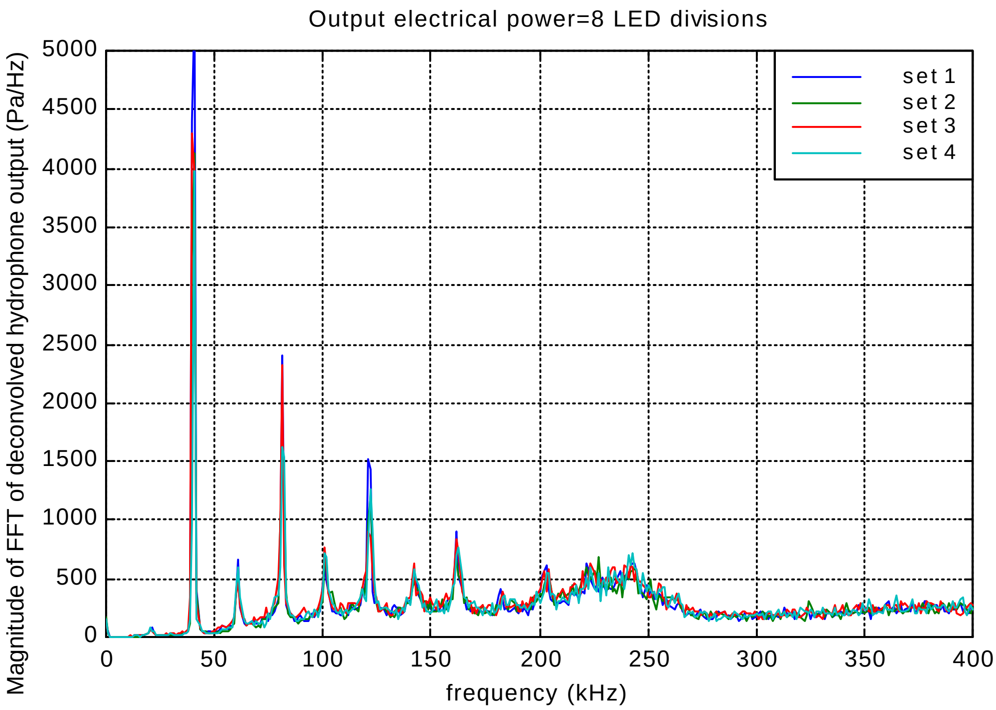

Figure 5.7: Spectra adjusted for hydrophone response at centre of tank for 4 sets of measurements; 40% of maximum output electrical power from generator

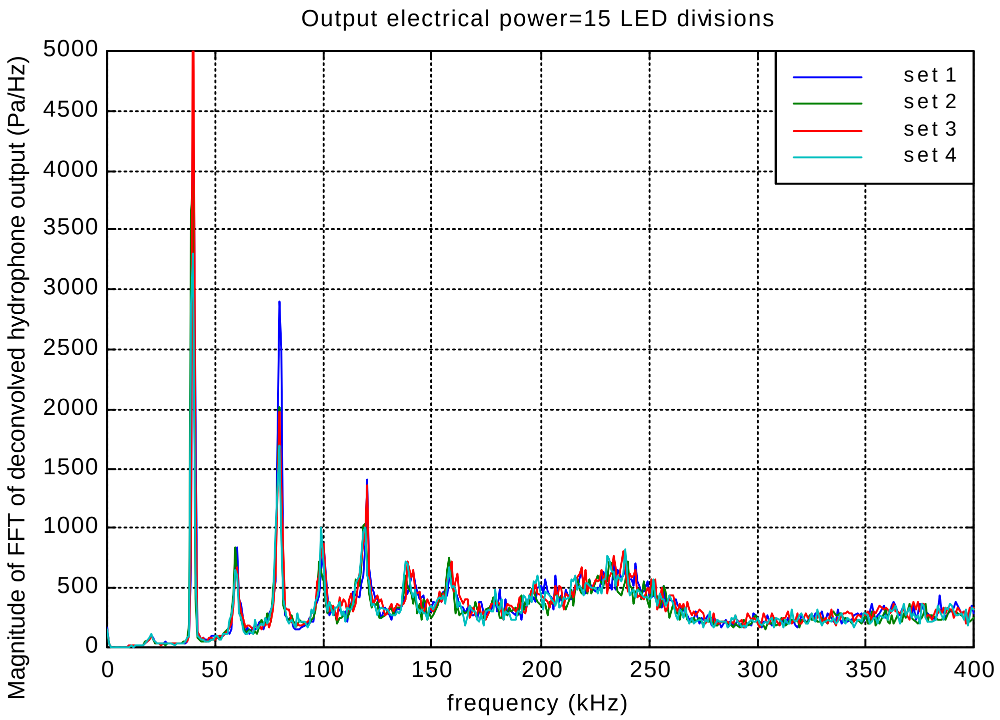

Figure 5.8: Spectra adjusted for hydrophone response at centre of tank for 4 sets of measurements; 75% of maximum output electrical power from generator

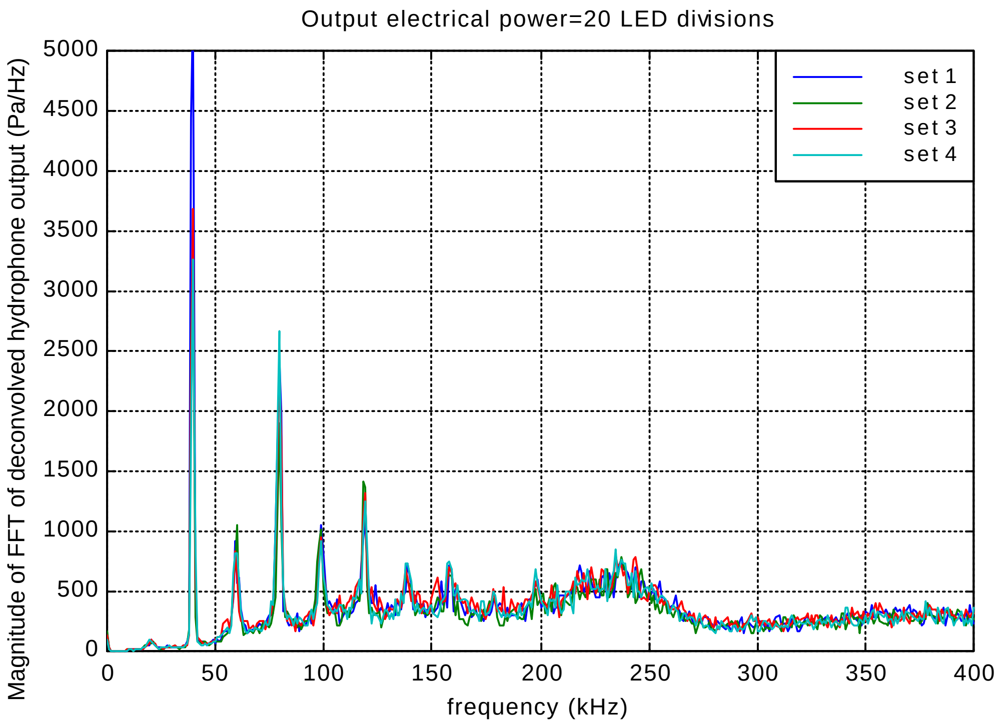

Figure 5.9: Spectra adjusted for hydrophone response at centre of tank for 4 sets of measurements; 100% of maximum output electrical power from generator

In the spectra adjusted for the hydrophone response, there still appears to be some of the hydrophone response present in the noise envelope. Due to the arguments brought forward earlier in this section, this is expected.

5.4.2.2 Estimation of the energy contained in the spectral envelope

In order to assess the reproducibility of the measurements, the acoustic energy *E* contained in the 0-400 kHz frequency band has been considered. This quantity is given by:

$$E = \int_{f_1}^{f_2} \left| \mathcal{F} \left[p(t) \right] \right|^2 df$$

where f_1 and f_2 are respectively 0 and 400 kHz in this case and $p(t)$ is the time domain pressure. $\mathcal{F}$ denotes the Fourier transform. Although this quantity does not have energy units, it is the standard way to evaluate the energy contained in a spectrum in signal processing. In order to evaluate the total energy, the limits of the integral in the above equation would have to be taken between -∞ and +∞.

Since it is the energy contained in the envelope that is to be determined (i.e. cavitation noise), it is of interest to remove the harmonic peaks. These are mainly thought to be the result of sound pressure produced by the transducers. Note that the collapse of cavitation events as well as stable cavitation events will also contribute to these peaks. As a first attempt, the following method was used. Initially, the spectrum is smoothed out by determining the *b* and *a* coefficients of a digital filter which best fits the squared spectrum in a least squares sense. It was usually found that a filter of order 135 was adequate. Once the magnitude of the frequency response function of this filter is obtained from these coefficients, this will produce a smoothed version of the spectrum. The peaks are then located, and a polynomial interpolation is carried out using the minima between two successive peaks. The area under the obtained plot is then obtained using a trapezoidal integration rule. An example is shown in Figure 5.10. Although this method is not extremely rigorous and does not allow for an inverse Fourier transform to be computed, it is considered to provide a reasonably accurate value when evaluating the energy in the spectrum due to inertial cavitation.

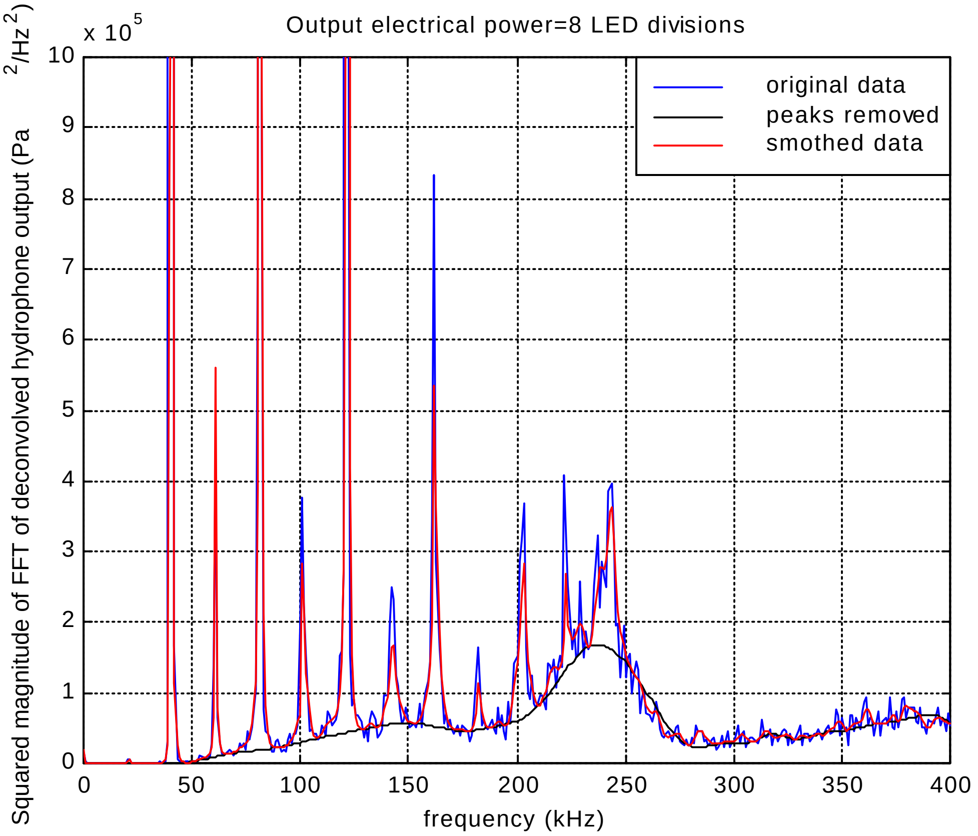

Figure 5.10: Squared spectrum, smoothed squared spectrum and estimated envelope. 40% of maximum electrical power output. First set of measurements

Calculations have been carried out for the 4 runs over the 17 power settings. Figure 5.11 shows the values of the integrals in the cases where the peaks have been removed.

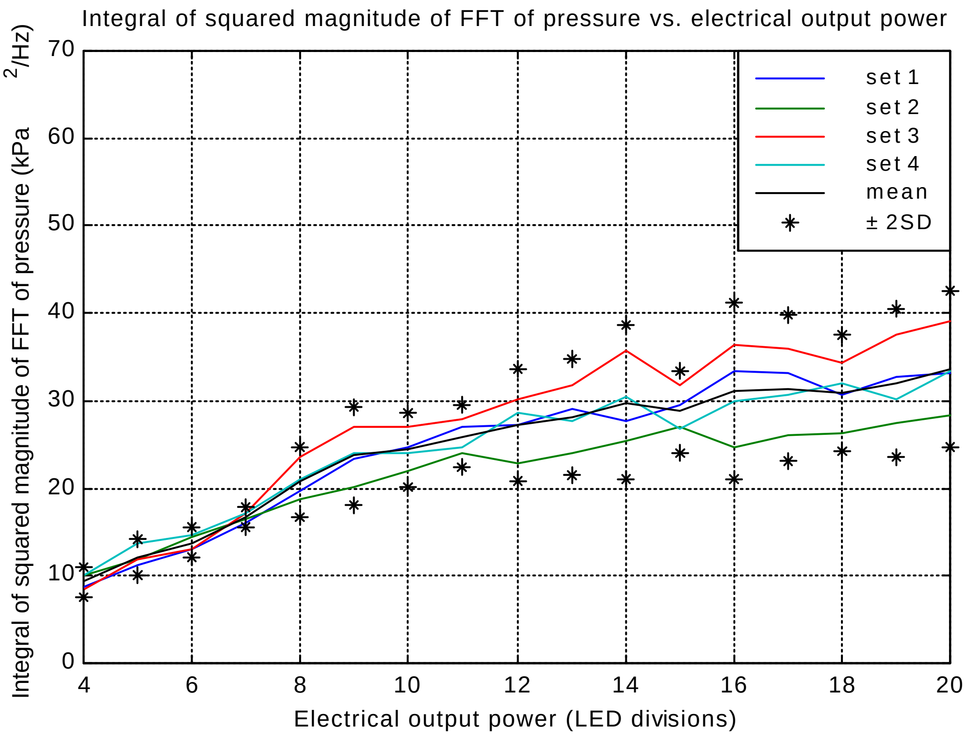

Figure 5.11: Energy contained in spectral envelope: SD denotes the standard deviation

It can be seen in Figure 5.11 that the mean increases by a factor of 3.59 between 20% and 100% of the maximum electrical power output. The average value of the mean of in this range is 2.47×10^7 Pa^2 Hz^{-1}. The increase of the energy of the spectra with power output is at first roughly linear but then tends to flatten out. This may indicate that the system is beginning to saturate and no longer behaves linearly. It may also show that at higher drive levels, more energy is contained at frequencies beyond the upper-limit of the hydrophone bandwidth.

In order to assess the reproducibility of the measurements, a graph obtained by evaluating twice the standard deviation as a percentage of the mean has been plotted and is shown below (see Figure 5.12).

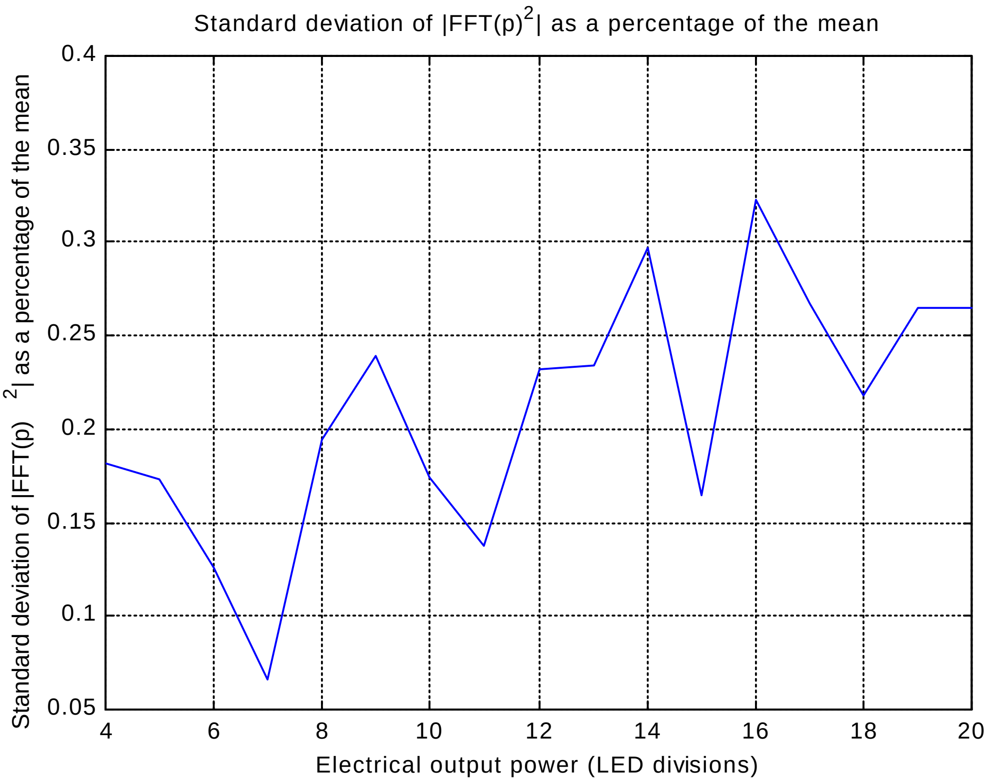

Figure 5.12: Reproducibility of measurement of energy contained in pressure spectrum between 0 and 400 kHz

It can be noted that on average, agreement is within ±21% of the mean value, with larger discrepancies between the 4 sets of measurements at higher power levels.

5.5 MEASUREMENTS ALONG THE DEPTH OF THE TANK

Measurements were carried out using B&K 8103 hydrophone submersed at different depths. It was initially placed at the centre of the tank in the *x*-*y* plane, with a *z*-axis coordinate of zero. This position corresponds to the surface of the water. The *z* coordinate was then varied. The orientation of the *z*-axis is chosen so that *z* increases positively with depth. The reference point on the hydrophone is at its centre, along its axis.

FFT's of the hydrophone output voltage have been acquired at power settings corresponding to 20% and 60% of the maximum output power from the signal generator (i.e. 4 and 12 lit LED's). The depth was varied in steps of 9 mm between 0 and 150 mm. This distance corresponds to approximately a quarter wavelength in water at 20°C at 40 kHz. In this case, 10 averages were used on the spectrum analyser.

Generally, the observations noted in Section 5.1 apply here. The energy contained in the 0-400 kHz frequency band was obtained in the same way as previously: the squared spectra were smoothed, the harmonic and sub/ultra-harmonic peaks removed. The integral in Section 5.4.2.2 is then numerically evaluated. Results are shown in Figure 5.13 for both power settings for two independent sets of measurements.

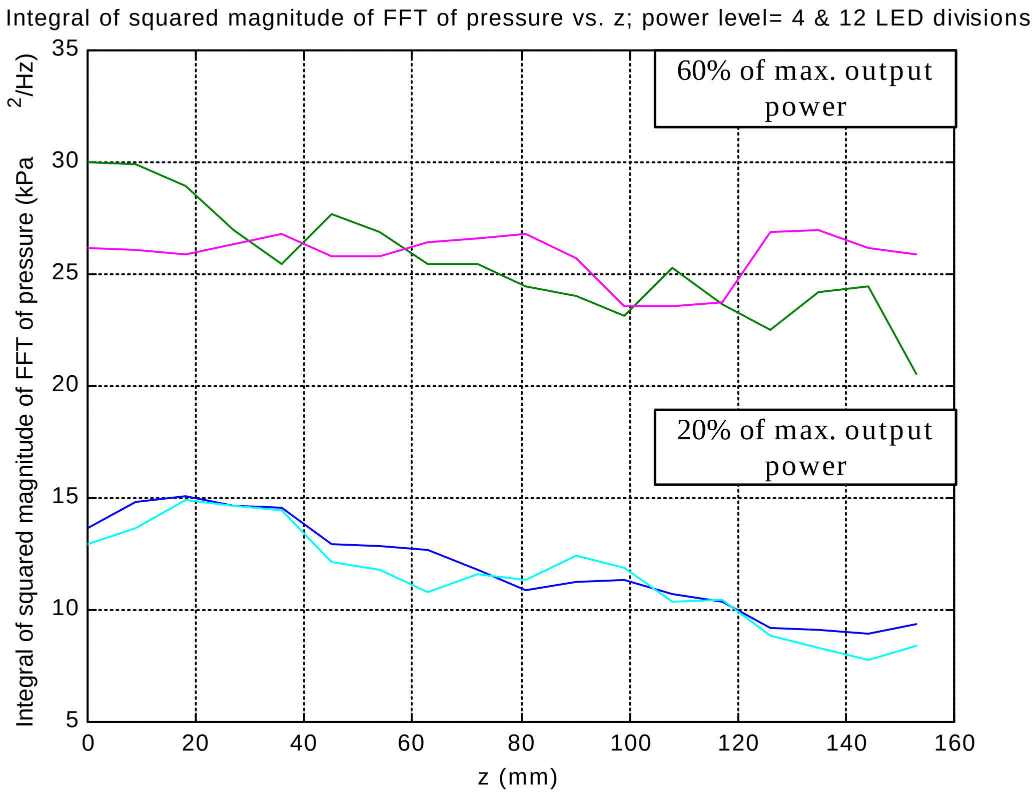

Figure 5.13: Energy in spectral envelope as a function of depth, with the cleaning vessel operating at 20% and 60% of maximum output electrical power. Position *z*=0 corresponds to the centre of the hydrophone active element being level with the water surface

Reproducibility is on average within ±10% of the mean. 10 averages were used when acquiring the spectra with a resolution bandwidth of 290 Hz, which possibly explains why the agreement between runs appears better than for the data in Section 5.1.

In considering other parameters as a function of position, the level of the fundamental can be expected to vary at a given position because slight differences in temperature will lead to variations in the wavelength, hence influencing the positions of pressure maxima and minima along the *z*-axis. In terms of selecting a parameter indicative of cavitation activity, the energy contained in the broadband noise envelope therefore appears to be more robust.

5.6 ADDITION OF SURFACTANT

In ultrasonic aqueous cleaning, surfactants are often combined with degassed/deionised water to increase the efficacy of the cleaning process. As mentioned in Section 2.4.3, the addition of surfactants will tend to lower the surface tension of the cleaning liquid.

Measurements have been carried out to investigate the effect of surfactant on the energy contained in the 0-400 kHz portion of the spectrum. The measurements reported in Section 5.4 were repeated for degassed water adding one teaspoon of Fairy Liquid® to the cleaning bath. Four independent sets were obtained. A graph of the spectra acquired at the centre of the tank adjusted for the hydrophone response for four sets of measurements taken at 40% of the maximum output electrical power from the ultrasonic generator is shown below (see Figures 5.14 and 5.15).

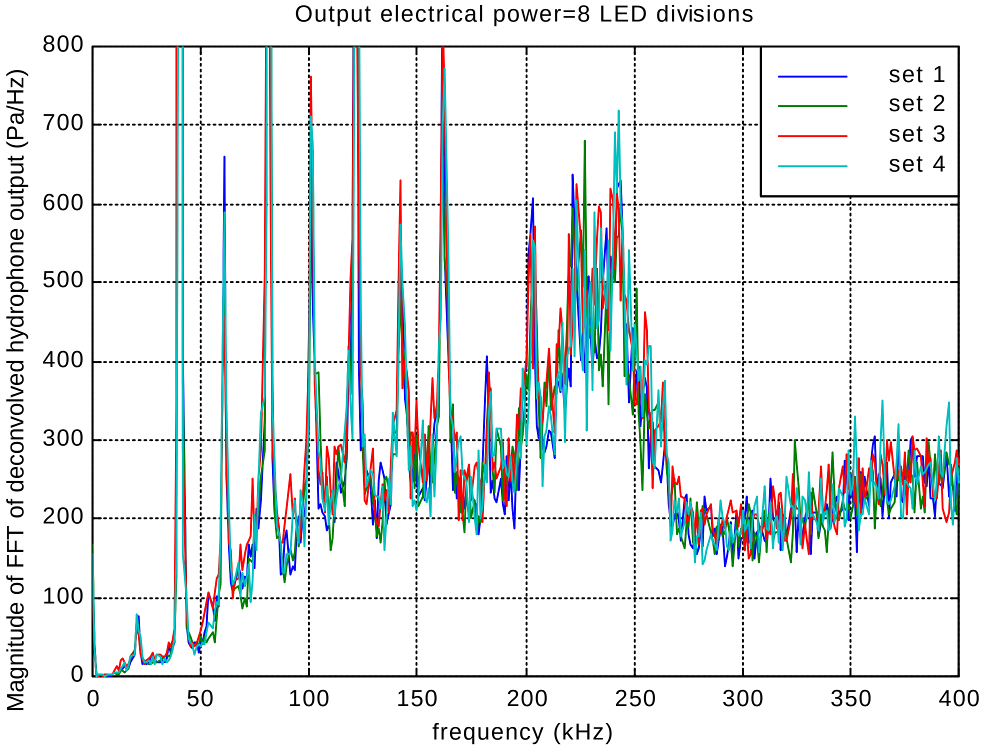

Figure 5.14: Spectra adjusted for hydrophone response at centre of tank for 4 sets of measurements in degassed water; 40% of maximum output electrical power from generator

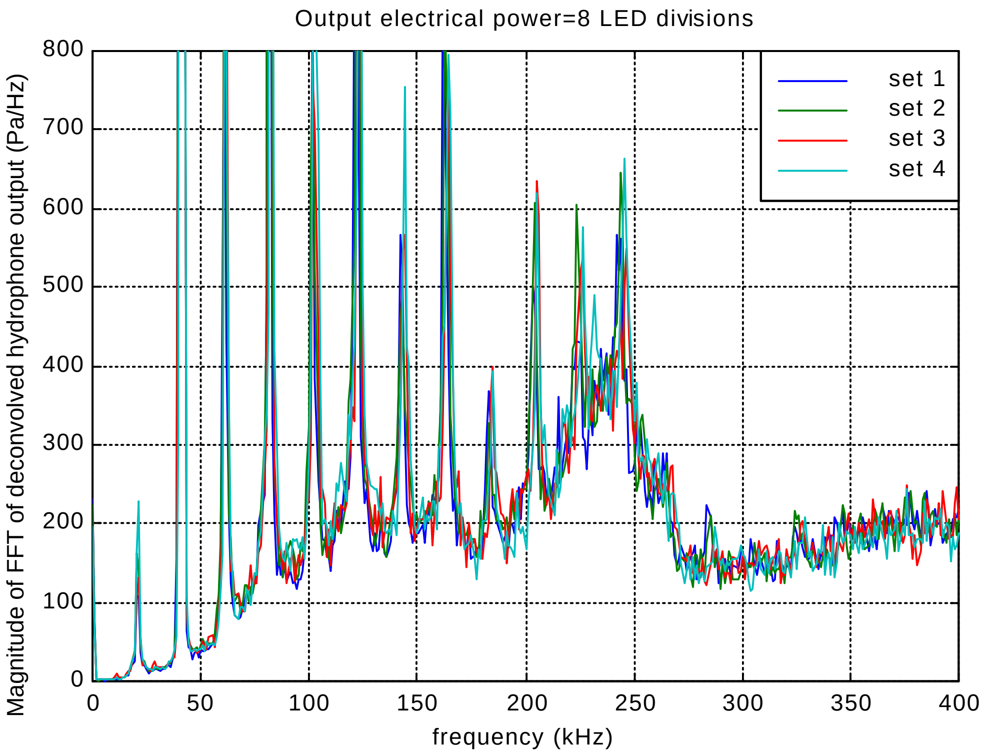

Figure 5.15: Spectra adjusted for hydrophone response at centre of tank for 4 sets of measurements in degassed water with surfactant added; 40% of maximum output electrical power from generator

The hydrophone spectra generally have a similar appearance to those acquired without surfactant, although their overall level is slightly lower. This will be quantified when comparing the energies in the spectra acquired with and without surfactant. This coincides with the findings in the literature review: as a result of adding surfactant, the lower surface tension of the medium allows bubbles to grow to a larger radius, hence resulting in a less violent form of cavitation (see Section 2.4.5).

The energy contained in the envelope of the spectra adjusted for the hydrophone response once the peaks have been removed is then computed as a function of drive level and a graph analogous to that in Figure 5.11 is obtained, Figure 5.16.

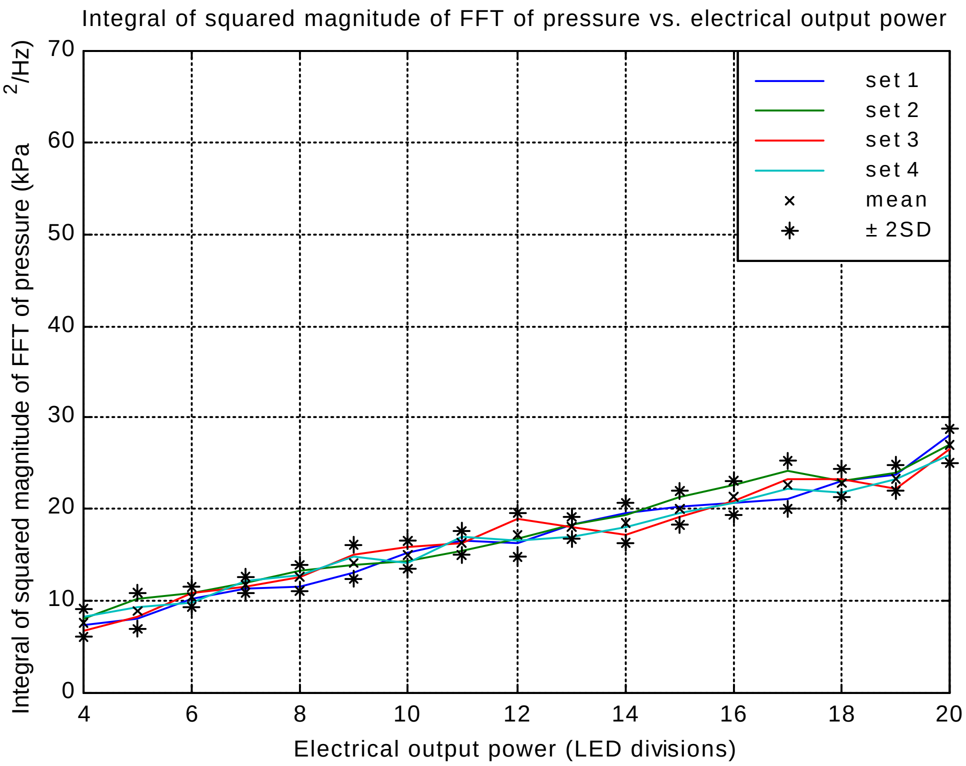

Figure 5.16: Energy contained in envelope of spectra: SD denotes the standard deviation

It appears that the variation in the energy contained in the 0-400 kHz frequency range of the spectrum with drive level exhibits similar characteristics to those in the case where no surfactant was used. The average energy increases by a factor of 2.85 between 20% and 100% of maximum output electrical power. However, as expected from what has been previously mentioned, the overall level of the mean is significantly lower than in Figure 5.11: 1.69×10^7 Pa^2 Hz^{-1} compared to 2.47×10^7 Pa^2 Hz^{-1}. The level of reproducibility is shown in terms of twice the standard deviation as a percentage of the mean (Figure 5.17).

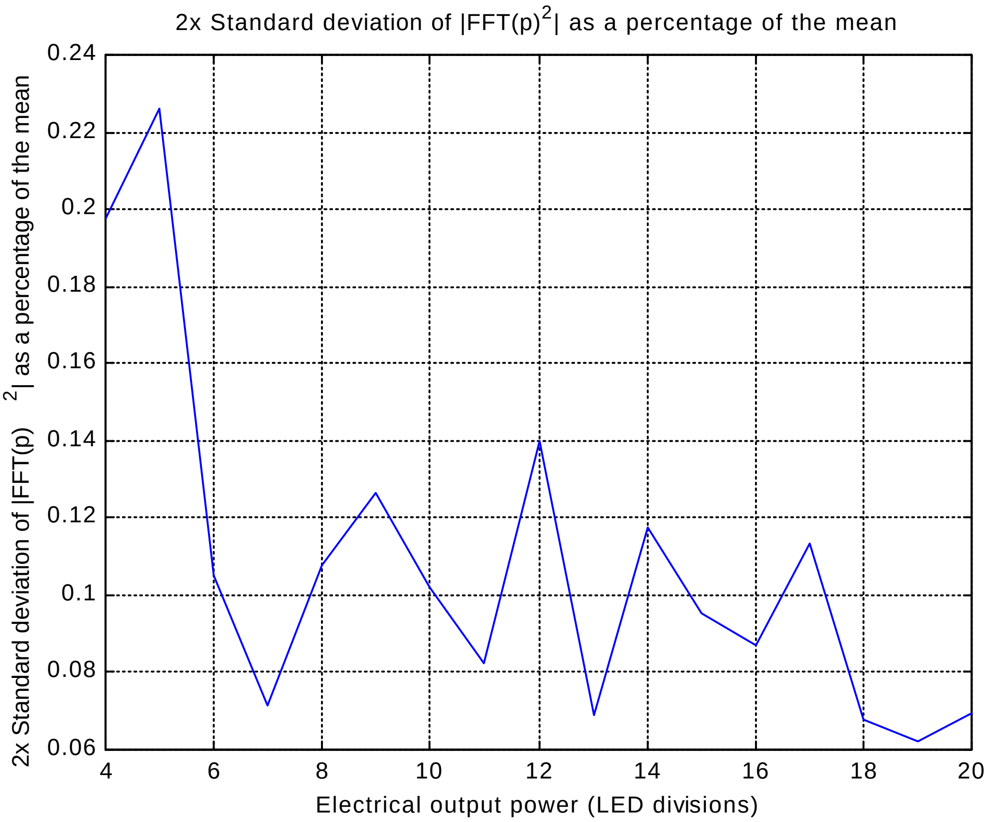

Figure 5.17: Reproducibility of measurement of energy contained in pressure spectra between 0 and 400 kHz

In comparing this with Figure 5.12, it appears that the level of reproducibility is considerably improved in the case with surfactant: better than 11% of the mean on average as opposed to 21% in the case where no surfactant was used.

5.7 MEASUREMENTS USING THE ITC-6128 HYDROPHONE

From single bubble dynamics calculations, it is known that when a bubble of a given radius is driven beyond a given driving pressure at a frequency of 40 kHz, it may radiate acoustic signals at frequencies beyond 1 MHz. In making these measurements, it was considered of interest to look at such higher frequency ranges, as they are less likely to contain any other acoustic pressure components other than those resulting directly from cavitation. Also, it is known that energy resulting from cavitation activity may be transferred to higher frequency components (24). The B&K 8103 hydrophone is quite limited in terms of its usable frequency range (the manufacturer specifies an upper frequency limit of 180 kHz). In contrast, the ITC-6128 has a broader usable frequency range: 200 kHz to 600 kHz. Although this does not quite encompass the frequency ranges of interest, it may be used above 1 MHz at the expense of a lower signal-to-noise ratio. This hydrophone is designed as a calibration transducer for high sonar frequency acoustic testing and other applications where high frequency measurements are needed. Its specifications are a follows:

- Resonance Frequency: 500kHz
- Usable Frequency Range: 200 kHz to 600 kHz
- Beam Pattern

    Horizontal: omni ± 2 dB

Vertical (over 270): 50° @ 40 kHz (toroidal)

A fine frequency free-field calibration between 10 kHz and 1 MHz was carried out for the ITC device (Figure 5.18). The frequency steps are as follows:

- 1 kHz between 10 and 200 kHz;
- 2 kHz between 200 kHz and 300 kHz;
- 5 kHz between 300 kHz and 500 kHz;
- 10 kHz between 500 kHz and 1 MHz.

Temperatures during the calibration varied between 18.4°C and 18.9°C. A cubic spline interpolation routine was used to estimate the data between 0 kHz and 1 MHz so as to obtain 401 equidistant points.

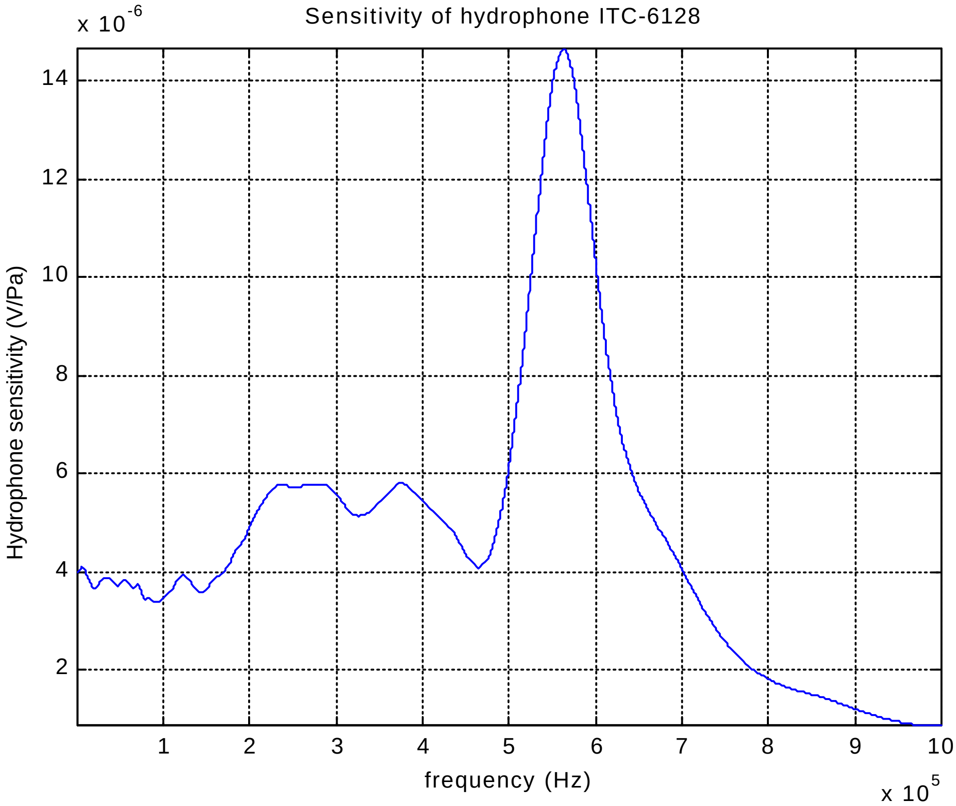

Figure 5.18: Hydrophone response obtained from fine-frequency calibration data.

The response exhibits one main resonance around 560 kHz. Note that this differs from the figure quoted by the manufacturer by about 12%.

Three sets of measurements were acquired at the centre of the tank under the same conditions as in Section 5.4. For these measurements, the I/O board was installed in the ultrasound generator, hence enabling a D.C. voltage which is proportional to the electrical output power to be monitored. The drive voltages for which the spectra were acquired are as follows:

0.67 V, 1.2 V, 1.6 V, 1.9 V, 2.34 V, 4.73 V, 6.72 V ,8.84 V and 10.47 V, with 10.47 V corresponding to 100% of the maximum output power (see Figure 5.19).

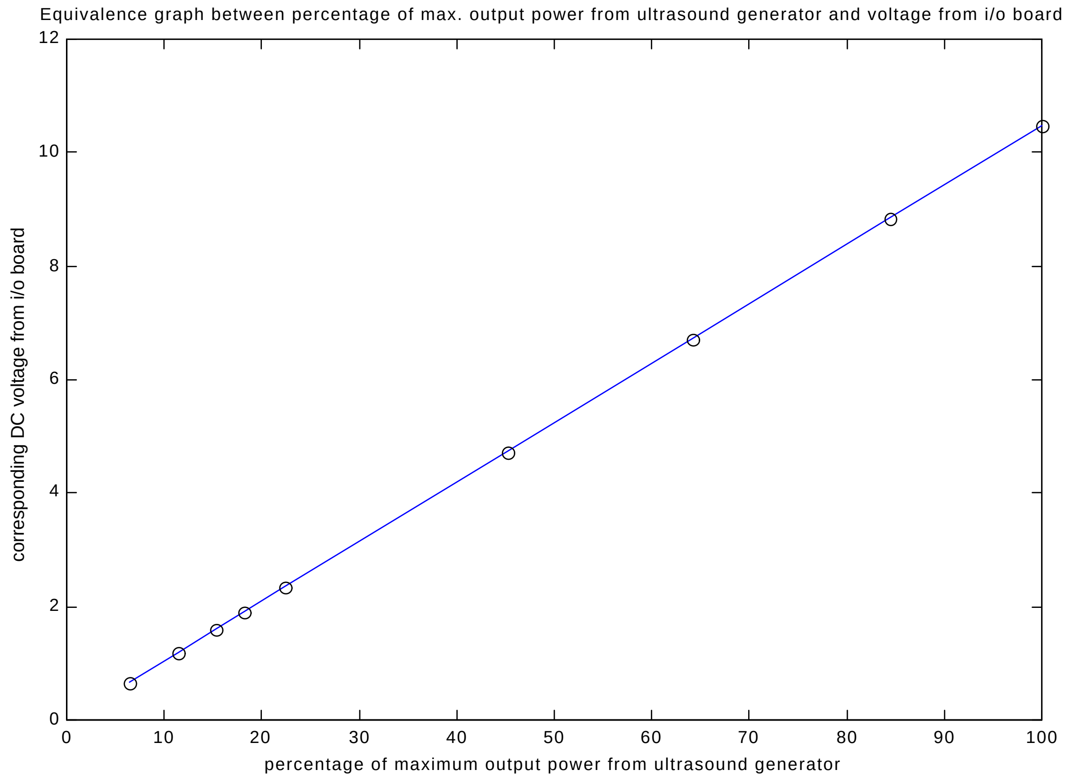

Figure 5.19: Equivalence graph between percentage of maximum output electrical power from the ultrasound generator and the DC voltage at the I/O board

Measurements at a drive voltage of 2.34 V are shown below (see Figure 5.20). This corresponds to about 22% of the maximum power output. 10.47 V corresponds to 100%.

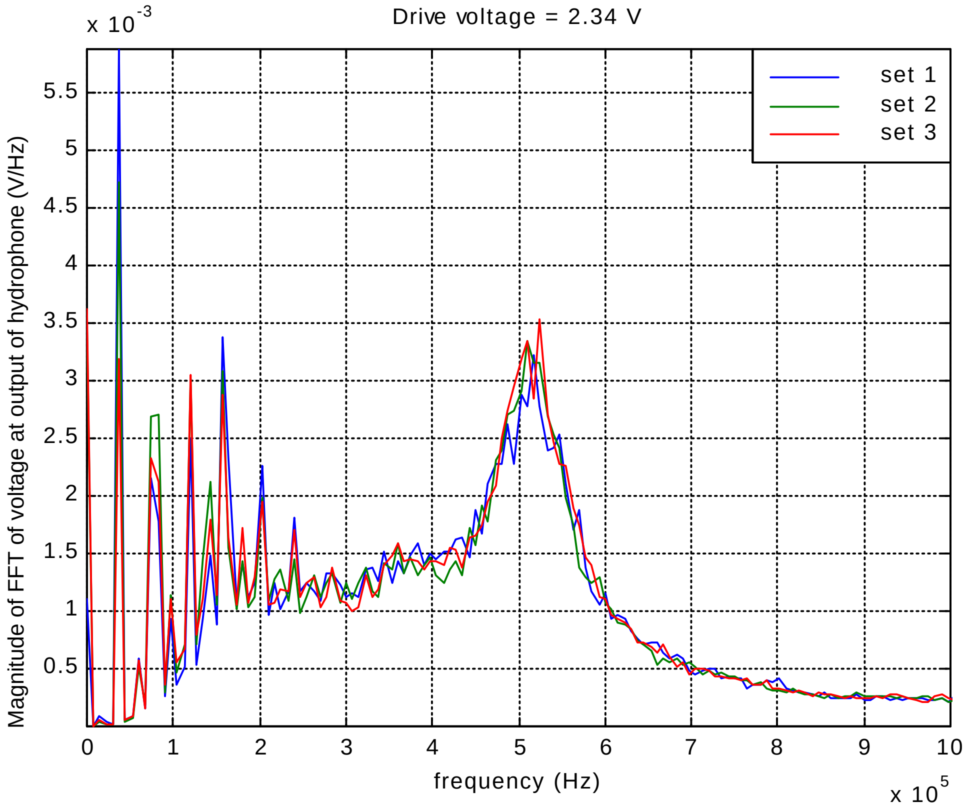

Figure 5.20: Hydrophone spectra at centre of tank for 3 sets of measurements, 2.34 V drive voltage

As in Section 5.2, the response of the hydrophone is clearly visible. It can be seen however that the main resonance as well as other features of the hydrophone sensitivity are somewhat shifted and/or distorted compared to the fine-frequency calibration data. To get a better idea of these effects, the spectra have been adjusted for the hydrophone response (Figure 5.21).

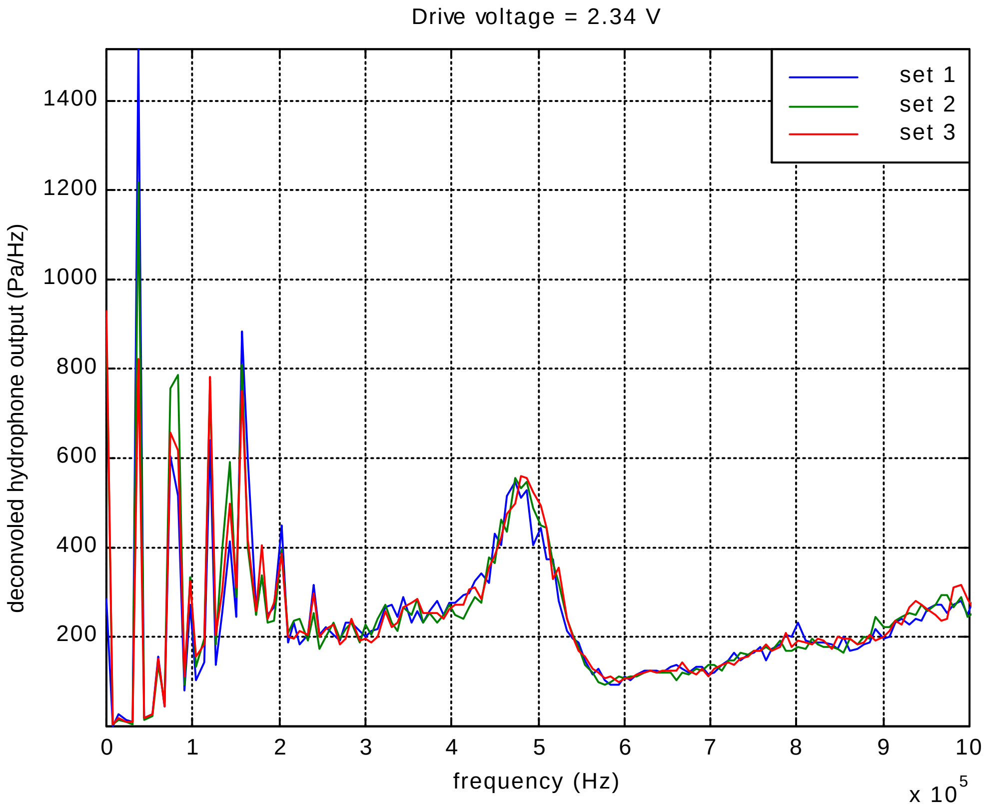

Figure 5.21: Spectra adjusted for hydrophone response at centre of tank for 3 sets of measurements, 2.34 V drive voltage

From Figure 5.21, it can be inferred that the response of the hydrophone within the cleaning bath appears to differ quite substantially from that obtained via a free-field calibration. The arguments given in Section 5.4.2.1 in the case of the B&K 8103 hydrophone also apply here, although further investigation is needed to clarify this point.

For this device, it was also considered of interest to analyse the spectra at frequencies between 750 kHz and 3 MHz. The major contribution to the acoustic spectra at those frequencies is considered to be from inertial cavitation, and so the removal of harmonic components due to transducer signals is not required. Although this frequency range extends beyond the upper frequency limit recommended by the manufacturer of the ITC-6128, the contents of the time domain signal above 600 kHz are clearly being measured albeit at a lower signal-to-noise ratio (Figure 5.22).

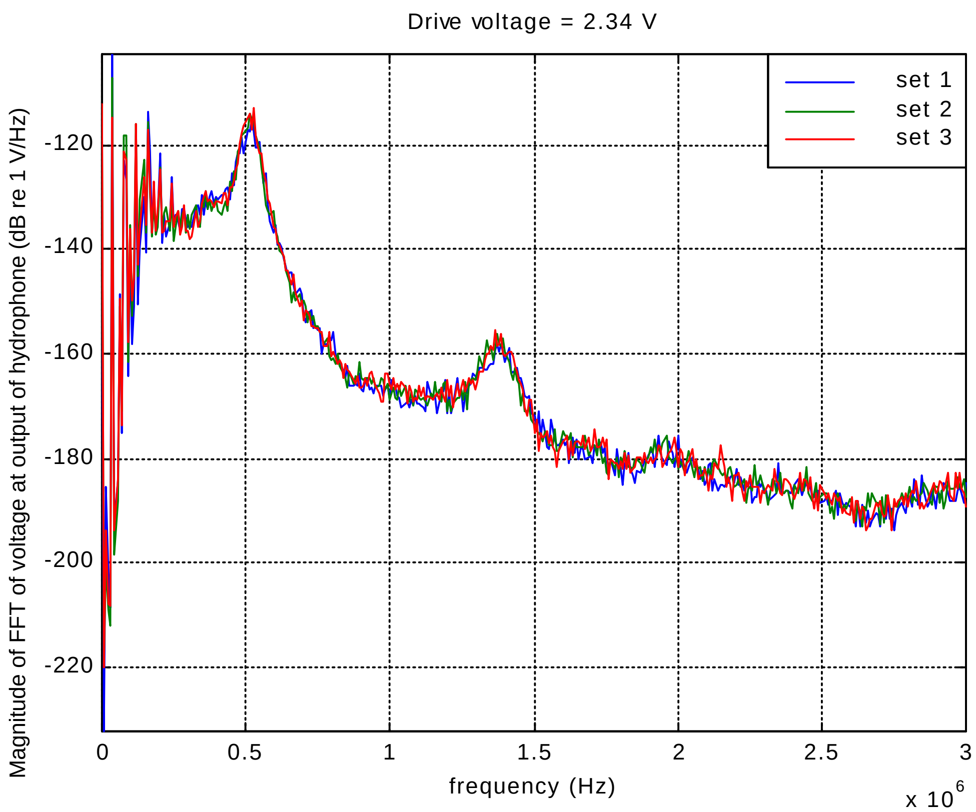

Figure 5.22: Hydrophone spectra at centre of tank for 3 sets of measurements plotted on a dB scale, 2.34 V drive voltage

It appears that in this case, adjusting the voltage spectra for the hydrophone response so as to obtain the pressure spectra is inappropriate as the hydrophone response issue is not addressed. It is the level of reproducibility that we wish to characterise, and this is not affected by the hydrophone response provided that the latter can be treated as a time-invariant system throughout the duration of the measurements. Hence, the energy contained in the voltage spectra between 750 kHz and 3 MHz will be considered as a function of drive voltage. The following plots have been obtained by estimating the area under the squared voltage spectra in this frequency range (Figure 5.23).

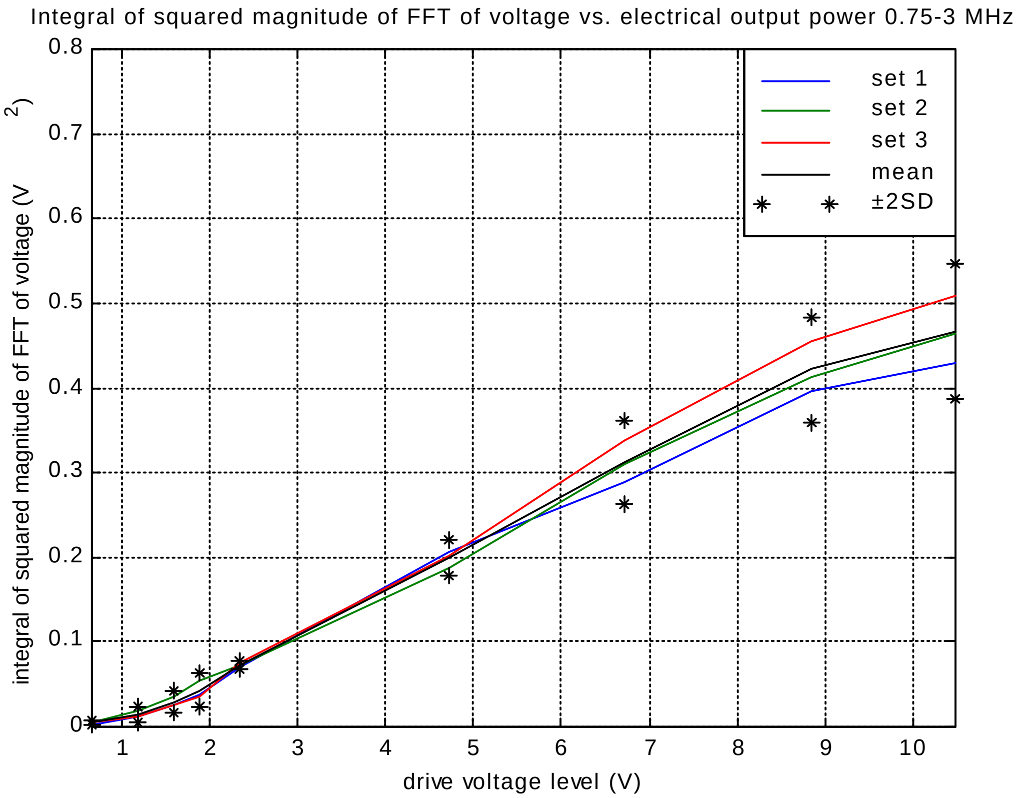

Figure 5.23: Energy contained in voltage spectra between 750 kHz and 3 MHz: SD denotes the standard deviation

A graph representing the reproducibility of the measurements is shown below (see Figure 5.24). It was obtained by evaluating twice the standard deviation as a percentage of the mean.

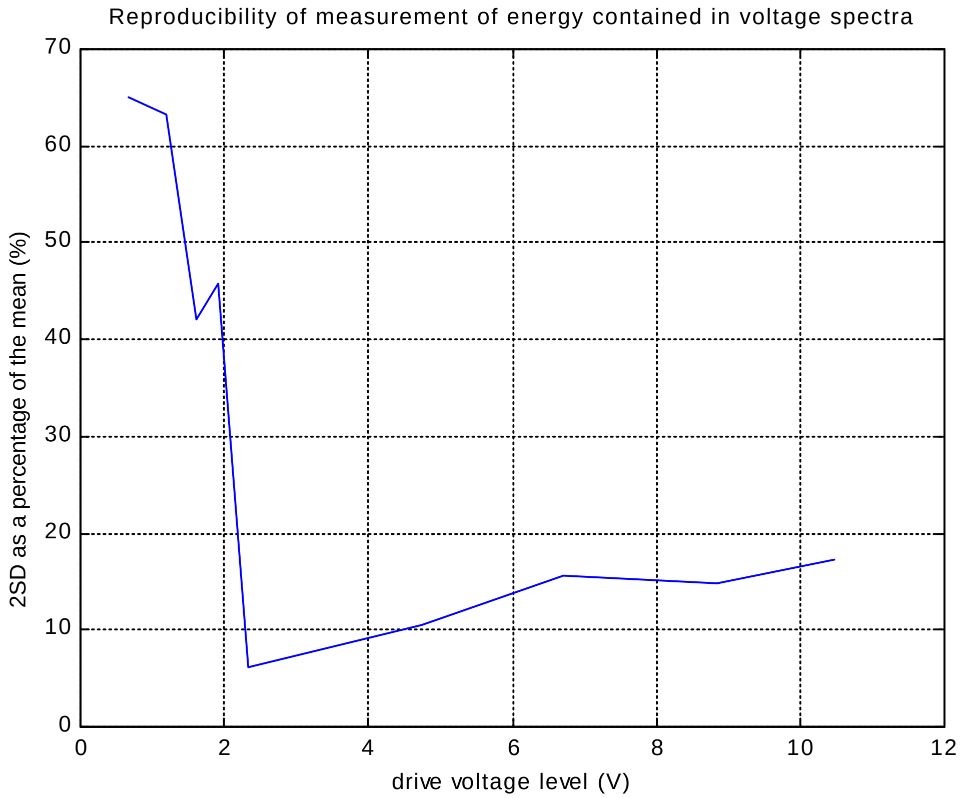

Figure 5.24: Reproducibility of measurement of energy contained in voltage spectra between 750 kHz and 3 MHz

Note that below a drive voltage of 2.34V (approximately 22% of maximum output power from the ultrasound generator), the reproducibility is rather poor. This is due in part to the fact that it is difficult to obtain a stable vessel drive voltage below 20% of the maximum output power. Above this level, the voltage measurement is more reliable and reproducibility is comparable to that obtained in the case of the measurements carried out with the B&K 8103 hydrophone with addition of surfactant: on average 12.9% for drive levels between 22% and 100% of the maximum output power.

5.8 MEASUREMENTS IN THE TIME DOMAIN

Whilst most data has been gathered using hydrophones in conjunction with the Hewlett Packard spectrum analyser, examining the frequency domain data, it was felt useful to evaluate the signals observed in the time domain, to examine the variation of signal levels, toneburst envelopes and so on.

The ITC hydrophone described above was positioned approximately in the centre of the cleaning vessel, and its output connected directly to a Tektronix TDS 784D oscilloscope. An RF coil pick-up was attached to the cable connecting the Branson drive unit to the cleaning vessel input to provide a monitor of the electrical drive signal applied to the transducers. Resulting waveforms were then acquired at two power settings (10% and 100%), for three separate input signals:

a) the drive waveform (as monitored by the RF coil);

b) the received acoustic waveform (from the ITC hydrophone);

c) the received hydrophone waveform, passed through a 4 MHz high-pass filter, so that the harmonic-dominated response at the low frequencies would be rejected.

The three pairs of results are shown in Figure 5.25. Note that the results have been self-normalised in each data set, so that they may be represented on equivalent amplitude scales. The actual drive signal amplitudes showed a difference of a factor of 3.2 between the 10% and 100% power cases, consistent with the power increasing ten-fold. The *x*-axes are in seconds.

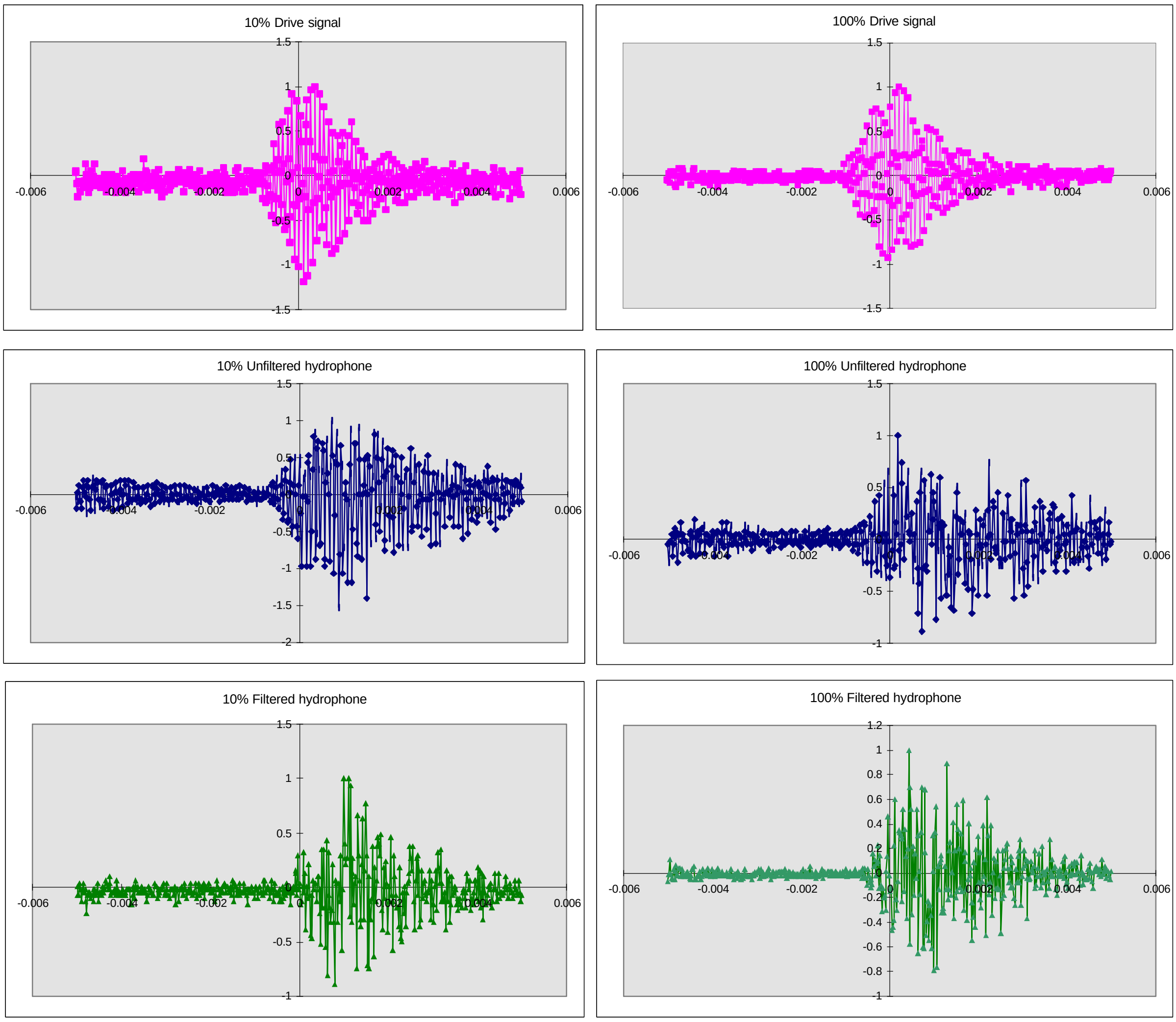

Figure 5.25: Three sets of time-domain waveforms, measured using an ITC hydrophone, for power settings of 10% and 100%

There are a number of features worthy of note in the drive signal plots (top). First, the amplitude modulation of the drive waveform is clearly seen. In this instance, only one burst from the Branson drive unit is shown, but examination of other waveforms acquired for slower timebase settings showed that it is the full burst which is depicted here – there is no further decay in level seen in the drive waveform. Second, the drive waveform is quite symmetrical about the time axis. Third, the envelope decays quite quickly, and so the electrical excitation time is of the order of 3 - 4 milliseconds or so.

The two unfiltered acoustic signal traces (middle) appear to start (in time) almost in synchronisation with the drive signal. This is also to be expected, as the propagation delay time from the bottom of the tank (where the transducers are) to the location of the hydrophone is around 100 μs, relatively insignificant on this timescale. The 10% drive level case appears more stable than the 100% case, with considerable signal level fluctuation seen in the latter.

The filtered acoustic signal traces (bottom) show an interesting feature – they start considerably later in time than the unfiltered case. Even allowing for some delay time in propagating through the passive filter box (estimated at a few tens of μs at most), there appears to be clear evidence of a delay of some 600 μs before any high frequency components are seen. This would fit in with the concept of a level threshold effect (as alluded to by the unfiltered response), and thus a delay-time corresponding to a number of driving pressure cycles before bubbles can reach a required size, collapse and produce broadband emissions. However, if this was the sole cause of the time delay, the interval before the high frequency signals were seen would be shorter for the 100% drive level than for the 10% level, which does not necessarily appear to be the case. To support this tentative conclusion, further measurements of this type will be carried out in deliverable 4.5.2.

5.9 SUMMARY

Preliminary tests were conducted so as to assess the general reproducibility of the experimental conditions in the Branson cleaning bath. The following factors were monitored: percentage of maximum output electrical power from signal generator, water level, water temperature (kept between 20°C and 28°C), dissolved oxygen content (kept below 6 parts per million) and hydrophone position.

Tests were completed for two sensors:

- B&K 8103 hydrophone

The 0-400 kHz frequency range was focused on. Good levels of reproducibility were observed for four independent spectra measurements at the centre of the tank using degassed water. The drive levels were varied between 20% and 100% of the maximum output electrical power from the signal generator in steps of 5%.

A fine-frequency free-field calibration of this hydrophone enabled the acquired spectra to be adjusted so as to obtain the magnitude of the pressure spectra. It was however noticed that the measured response obtained from the calibration does not quite match the response observed in the cleaning bath. Operating conditions are suspected to be responsible for this, although further investigation is needed to confirm this.

An estimate of the energy due to cavitation activity contained in the spectra in the 0-400 kHz frequency range was then obtained by squaring the spectra and removing the peaks due to harmonics and sub / ultra-harmonics. This was evaluated as a function of drive level. It was found that the average reproducibility for the four independent sets of measurements was within ±21% of the mean value. The average level of the energy over this range of output powers is 2.47×10^7 Pa^2 Hz^{-1}.

A depth scan at two power levels for two independent sets of measurements revealed that the average reproducibility was within ±10% of the mean value.

Four independent sets of data were acquired at the centre of the tank after one teaspoon of Fairy Liquid ® had been added to the degassed water. The average reproducibility of the energy contained in the spectra once the peaks have been removed was within 11% of the mean. The average level of the energy is 1.69×10^7 Pa^2 Hz^{-1}, which is significantly lower than in the case without surfactant.

- ITC-6128 hydrophone.

Three independent sets of measurements at the centre of the tank were produced using degassed water. Use of the I/O card enabled the drive level to be reduced to about 6% of the maximum output electrical power and the electrical power output from the generator to be monitored more accurately.

A fine-frequency calibration of this hydrophone was produced. Due to large discrepancies between the response of the hydrophone in the cleaning bath and that obtained from the calibration (12% frequency shift in the main resonant frequency), the energy contained in the voltage spectra was computed between 0.75 and 3 MHz. There are no visible peaks due to harmonics and sub/ultra-harmonics within this frequency range so computing this energy is straightforward.

Measurements obtained for drive levels below 20% of the maximum output electrical power from the generator appear unreliable due to difficulties in obtaining a stable voltage reading from the I/O board. Between 22% and 100% of the maximum output electrical power however, the average reproducibility as a percentage of the mean is 12.9%.

Measurements made in the time domain using the ITC hydrophone showed that the received acoustic signal at high frequencies appeared to be delayed in time relative to the drive signal and the fundamental frequency component, illustrating the expected conclusion that a number of acoustic cycles are required before bubble collapse occurs.

6 SUMMARY AND CONCLUSIONS

This report has described the tasks completed in the first phase of the project AK040510. A literature review has been carried out, outlining the importance of monitoring and controlling the following parameters:

- water quality/quantity, in particular dissolved gas and particulate content, temperature, and water level;
- frequency;
- the output voltage from the signal generator as an indicator of the acoustic power output.

Specifications for the water management system, the scanning rig, the enclosure and the software to be used in conjunction with the cleaning vessel have been described, with modifications made to the ultrasonic generator used to drive the transducers in the cleaning bath extending the range over which characterisation measurements may be made. The infrastructure required to realise the concept of a reference ultrasonic cleaning vessel has thus been put in place.

A limited set of preliminary measurements on the cleaning vessel have been carried out at various bath drive levels for two different hydrophones positioned in turn at the centre of the tank, and also as a function of position along the depth of the tank. The magnitude of the acoustic spectra have been processed in order to account for the hydrophone response in each case. It was then attempted to obtain a value for the energy content of the spectra between 0 and 400 kHz for a B & K device, and at higher frequencies for an ITC device. The effect of surfactants on signal levels and reproducibility of results has also been examined. Overall, the reproducibility of the energy content of cavitating bubbles at various drive levels has been demonstrated to be in the range of 12 to 21%, which is very encouraging. The remaining deliverables may thus be carried out on a confident basis.

7 ACKNOWLEDGEMENTS

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8 REFERENCES

1. DTI Report, 1991. *Cleaner Technologies in the UK.*

2. FLYNN, H. G. *Physics of Acoustic cavitation in liquids*, in Physical Acoustics, vol .1 Part B (W. P Mason ed., Academic Press, NY 1964) 57-172

3. NEPPIRAS, E. A. *Acoustic cavitation*, Phys. Rep., 1980, **61**, 160-251.

4. LEIGHTON, T.G. *The Acoustic Bubble*, Academic Press, London, (1994).

5. APFEL, R. *Sonic effervescence: a tutorial on acoustic cavitation.* J. Acoust. Soc. Am. **101**, 3, 1227-1237 (1997).

6. VAUGHAN, P. W., LEEMAN, S. *Transient cavitation: fact or fallacy?* Ultrasonics International 89 Conference Proceedings, 1259-1264 (1989).

7. LEIGHTON, T. G. *A strategy for the development and standardisation of measurement methods for high power/cavitating ultrasonic fields: review of cavitation monitoring techniques,* ISVR Technical Report No. 263, January 1997

8. International Electrotechnical Commission, IEC 61102:1991, *Measurement and characterisation of ultrasonic fields using hydrophones in the frequency range 0.5 MHz to 15 MHz.*

9. International Electrotechnical Commission, IEC 61157:1992, *Requirements for the declaration of the acoustic output of medical diagnostic ultrasound equipment.*

10. Food and Drug Administration, FDA 510(k): 1985, *Guide for measuring and reporting acoustic output of diagnostic ultrasound medical devices.*

11. International Electrotechnical Commission, IEC 61689:1992, *Ultrasonics - Physiotherapy systems - performance requirements and methods of measurement in the frequency range 0.5 MHz to 5 MHz.*

12. EC Medical Devices Directive (93/42/EEC), Official Journal of the European Communities, **36** (L 169).

13. International Electrotechnical Commission, IEC 61846:1998, *Ultrasonics - Pressure pulse lithotripters - Characteristics of fields.*

14. International Electrotechnical Commission, IEC 61847:1998, *Ultrasonics - Surgical systems - Measurement and declaration of the basic output characteristics.*

15. POHLMAN, R. G., HERBERTZ, T. J. M. *A new instrument for measuring the ultrasonic energy density in liquids,* Ultrasonics for Industry Conference Papers 1970.

16. International Electrotechnical Commission, IEC Document SC29D/WG1(Secretary)11, October 1977. *Report on results of preliminary evaluation of the Integrating Probes.*

17. International Electrotechnical Commission, IEC 60886:1987, *Investigations on test procedures for ultrasonic cleaners.*

18. ZEQIRI, B., HODNETT, M., LEIGHTON, T. G. *A strategy for the development and standardisation of measurement methods for high power cavitating ultrasonic fields: final project report,* NPL Report CIRA (EXT) 016, 1997.

19. HODNETT, M., ZEQIRI, B. *A strategy for the development and standardisation of measurement methods for high power/cavitating ultrasonic fields: review of high power field measurement techniques,* Ultrasonics Sonochemistry, **4**, 273-288, 1997.

20. LEIGHTON, T. G. *The Acoustic Bubble*, pp73-74, Academic Press, London, (1994).

21. BUSNAINA, A. A., GALE, G. W., KASHKOUSH, I. I. *Ultrasonic and Megasonic Theory and Experimentation*, The Magazine of Critical Cleaning Technology, 13-19, April 1994.

22. CAE Blackstone Ultrasonic Cleaning Fundamental Theory and Application website.

23. AWAD, S.B. *Ultrasonic cavitation and precision cleaning*, The magazine of critical cleaning Technology, 12-17, November 1996.

23. YOUNG, F. R. *Cavitation*, p164, McGraw-Hill, London, 1989.

24. TM Associates Precision Cleaning Systems website, http://www.precisioncleaningweb.com

25. NIEDERDRÄNK, T., WIESLAND, B. *Temperature Dependent Behaviour of a Cavitation Bubble Field,* Acustica, **84**, 425-431 (1998).

26. LEIGHTON, T. G. *The Acoustic Bubble*, p421, Academic Press, London, (1994)

27. Industrial Cleaning Systems Inc. website, http://www.industrialcleaningsyst.com/clean.htm

28. LEIGHTON, T. G. *The Acoustic Bubble*, p76, Academic Press, London, (1994).

29. LEIGHTON, T. G. *The Acoustic Bubble*, p56, Academic Press, London, (1994).

30. ELDER, S. A., *Cavitation Microstreaming,* J. Acoust. Soc. Am., Vol 31, No.1, **54** (1959).

31. DTI Press Release P/97/488: *LASER to provide National Physical Laboratory fit for next millennium*, July 1997.

32. LEIGHTON, T. G. *The Acoustic Bubble*, p413, Academic Press, London, (1994).

33. YOUNG, F. R. *Cavitation*, p116, McGraw-Hill, London, 1989.

34. YOUNG, F. R. *Cavitation*, p121, McGraw-Hill, London, 1989.

35. GUTH, W. *Acustica*, **6**, 532, 1956.

36. LAUTERBORN, W., CRAMER, E. *Subharmonic route to chaos observed in acoustics,* Phys. Rev. Lett., **47**, 1445-1448, 1981.

37. LEIGHTON, T. G. *The Acoustic Bubble*, p415, Academic Press, London, (1994).

38. NEPPIRAS, E. A. *Acoustic cavitation*, Phys. Rep., **61**, 159-251, 1980.