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Report

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Industrial trialling of a novel sensor providing objective measurements of the effectiveness of high power ultrasonic equipment –

Final Project Report

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Department for Innovation, Universities & Skills

Industrial trialling of a novel sensor providing objective measurements of the effectiveness of high power ultrasonic equipment – Final Project Report

Mark Hodnett and Bajram Zeqiri
Quality of Life Division

ABSTRACT

This report describes in detail the work carried out under Joint Industrial Project 2004_23, entitled "**Industrial trialling of a novel sensor providing objective measurements of the effectiveness of high power ultrasonic equipment".** It describes in detail the design, manufacture and testing of the cavitation sensors, and of new detection electronics to analyse the sensor signals and provide near real-time information to users.

It also includes details of an industrial trialling exercise carried out by three UK organisations, in which they used the developed sensors and signal processing electronics to assess the cavitation activity produced by their systems. This provided a critical analysis of the sensor-electronics systems, and also provided collaborators from the UK high power ultrasound community with the opportunity to test the novel technology, and compare it to existing cavitation assessment techniques.

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1 EXECUTIVE SUMMARY

This report describes in detail the work carried out under Joint Industrial Project 2004_23, entitled "**Industrial trialling of a novel sensor providing objective measurements of the effectiveness of high power ultrasonic equipment".** It commences with the technical background to the project, the industrial demand for cavitation monitoring techniques and the concept behind the cavitation sensor. It then goes on to describe in detail the design and manufacture of the sensors (highlighting the significant contribution made to the project by the partners), and testing of the cavitation sensors and detection electronics using NPL's reference facilities.

Finally, it includes details of an industrial trialling exercise carried out by three UK organisations, in which they used the developed sensors and signal processing electronics to assess the cavitation activity produced by their systems. This invaluable part of the project provided a critical analysis of the sensor-electronics systems which will benefit future designs, and also provided collaborators from the UK high power ultrasound community with the opportunity to test the novel technology, and compare it to existing cavitation assessment techniques.

2 BACKGROUND

The application of high power ultrasound to liquid systems, in order to effect processes such as cleaning and sonochemistry has been an established industrial, medical and research practice for over 40 years. The primary driver behind these processes is acoustic cavitation, which may be described briefly as the growth, oscillation and subsequent collapse of pre-existing microbubbles in solution, under the influence of an applied acoustic field.

To optimise industrial processes and improve efficacy of medical treatments, there is a long-standing requirement for cavitation detection techniques. Many approaches have been used, ranging from chemical dosimetry and light emission to material erosion (1), but to date, none have been found to be sufficiently impartial, robust or repeatable to develop into standard methods (2).

In recent years, NPL has made significant progress in developing such methods based on passive detection of acoustic emissions from oscillating and collapsing bubbles, using a novel sensor developed to proof-of-principle stage through a Strategic Research Project. The basis of the sensor concept and a summary of the progress to date are described in Section 2.1.

2.1 THE NOVEL CAVITATION SENSOR

Oscillating and collapsing bubbles undergoing acoustic cavitation emit sound waves. The novel sensor considered in this project, developed as part of an NPL Strategic Research (SR)* project, detects these acoustic signals. Their special features are a wide measurement bandwidth (they are able to monitor signals up to 10 MHz) and spatial sensitivity, both of which are critical to reliably characterise cavitation. Sensor proof-of-principle has been demonstrated through both SR and DTI NMSD unit programme funding, but only for a limited number of experimental conditions, with the sensors having been developed through to prototype stage.

* The novelty and potential industrial impact of the sensor was acknowledged when a paper describing its concept and proof-of-principle won the IEEE Ultrasonics, Ferro-electrics and Frequency Control (UFFC) outstanding paper award for 2003.

The commonly used test applied by manufacturers and required by NHS HTM 2030 for checking the performance of cleaning vessels used in the process of sterilising medical instruments, is to immerse a thin layer of aluminium foil in the vessel of interest. Cavitation bubble collapse, occurring close to the foil surface, leads to holes being punched in the foil, and assessing the extent of eroded material provides a purely qualitative observation of whether cavitation is occurring. However, whilst useful, it has been impossible to standardise this test into an accepted objective method. Recent work carried at NPL (3) has demonstrated that the cavitation sensor provides a characterisation capability that correlates well with aluminium foil erosion results, indicating the sensor output relates closely to the effectiveness of the cleaning process. This strongly suggests that the novel sensor will provide the basis of a standardised method of measurement.

3 PROJECT OBJECTIVES

The agreed project proposal is shown in Appendix A. The three main objectives of the project are to:

- manufacture five cavitation sensor – electronic module units which may be considered pre-production systems;

- complete industrial trialling of the units, in a range of applications, providing an objective assessment of the performance of the sensors;

- collate and critically analyse the trialling results, feeding knowledge gained into an improved specification of the cavitation sensor, significantly shortening time-to-market.

These are broken down into 5 Work Packages, and the report discusses progress against these:

WP1 Development of improved, ruggedised cavitation sensors and electrodes *4 months*

WP2 Manufacture of five complete systems, comprising cavitation sensor and integrated electronics *6 months*

WP3 Testing of cavitation sensor systems at NPL *7 months*

WP4 Trialling of cavitation sensors by collaborators *11 months*

WP5 Final report, summarising trialling measurements *12 months*

4 WP1 - SENSOR DEVELOPMENT

4.1 SENSOR ELECTRODE

The polyvinylidene fluoride (*pvdf*) film used was provided by MSI Inc., and was of thickness 110 μm (giving a theoretical resonance at around 10 MHz). Electrical connections were made to either side of the centre line of the strip via 1.5 mm nylon bolts and metal rings soldered to the wires of the coaxial cable. This connection technique, whilst somewhat bulky, proved to be the most robust method. The cable length used in each case was 102 cm. In total, 45 electrode strips were made according to this design, and used to produce cavitation sensors.

4.2 MOULDED CAVITATION SENSOR

The construction and dimensions of the cavitation sensor are shown in Figure 4.1. The principles behind the sensor design, the material properties and concept validation are described in detail in the publications by Zeqiri et al (4, 5), and so are not repeated here.

In brief, the sensor operates as follows: the sensor consists of a sandwich of polyurethane layers, in between which is a 110 μm layer of *pvdf* that detects acoustic signals emitted by oscillating and collapsing bubbles. The surrounding polyurethane cavitation shield layer is strongly attenuating to signals produced by bubbles in the megahertz frequency range. This provides the sensor with spatial resolution, as any detected signals above 1 MHz (achieved through selective electrical filtering of the sensor signal) must originate from cavitation events occurring within the fluid volume enclosed by the cylindrical construction. Additionally, the properties of the cavitation shield are such that acoustic signals below 50 kHz are attenuated by less than 2 dB, and so the perturbation caused by the sensor to the driving field of the system under test is minimised. The polyurethane protective layer around the inside of the sensor (which is acoustically impedance matched to water) minimises the likelihood of cavitation erosion damaging the *pvdf* layer.

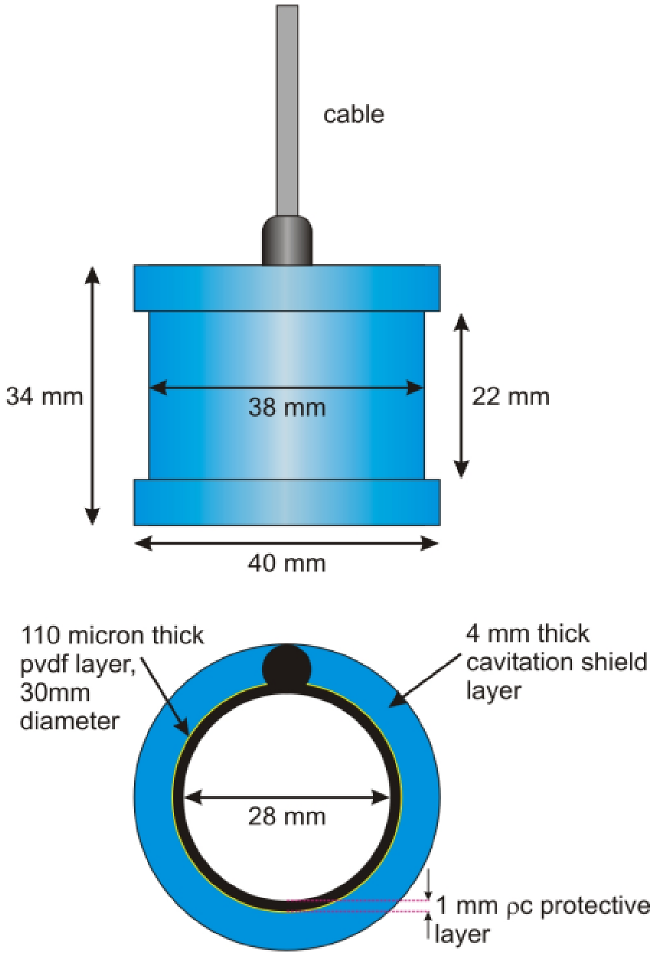


Figure 4.1: Schematic of cavitation sensor construction

The encapsulation process to deposit the two polyurethane layers was carried out using a mould tool that was constructed that enabled sensors to be produced in multiples of five. Initially, one set of five strips was provided, and the first batch of sensors made. Following successful initial electrical and acoustical testing, a further batch of thirty sensors was made.

To examine the consistency of manufacture of all sensors, the electrical impedance of the encapsulated sensors was determined, with each sensor immersed in deionised water, and the testing carried out in a random order. The analysed data is shown in Figure 4.2, and is presented as the capacitance of each device at 4 MHz (note that sensor 30_01 was not tested during this process). The figure shows excellent manufacturing repeatability, with sensor 30_25 being the only device that fell outside ±2 standard deviations of the mean, and only marginally so. It was decided to wait for the results of the acoustic performance tests before deciding whether this sensor should be used further in the project.

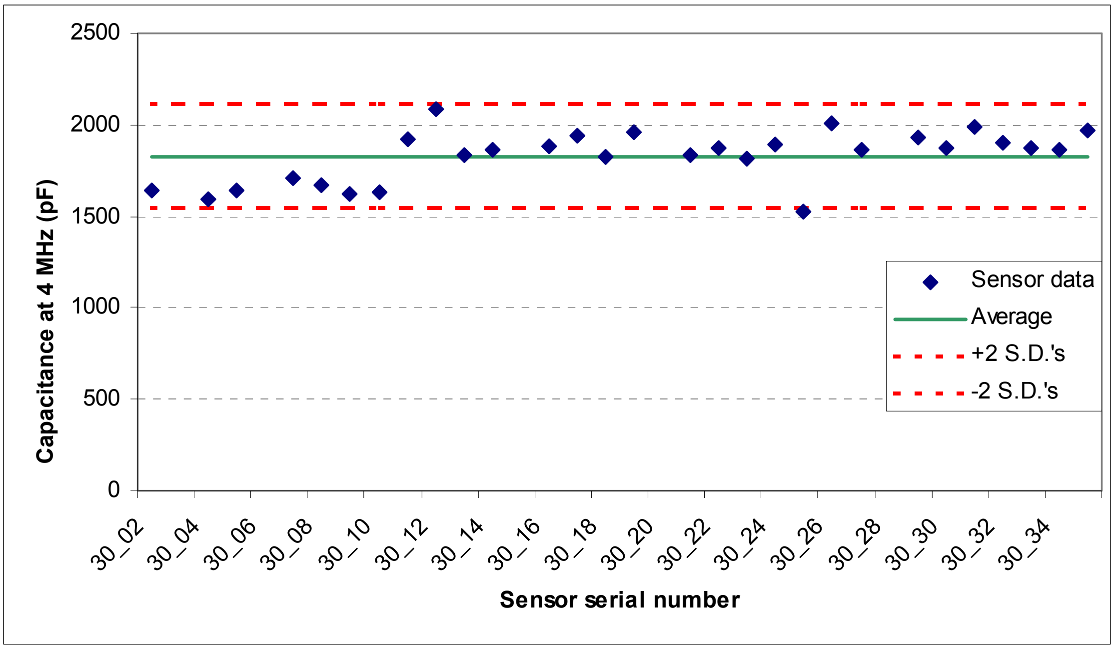


Figure 4.2: Capacitance of each cavitation sensor at 4 MHz, with average and standard deviations over the full sensor set

4.3 SENSOR TESTING

Following the electrical tests, the manufactured encapsulated cavitation sensors were tested acoustically using a purpose-designed rig, shown schematically in Figure 4.3.

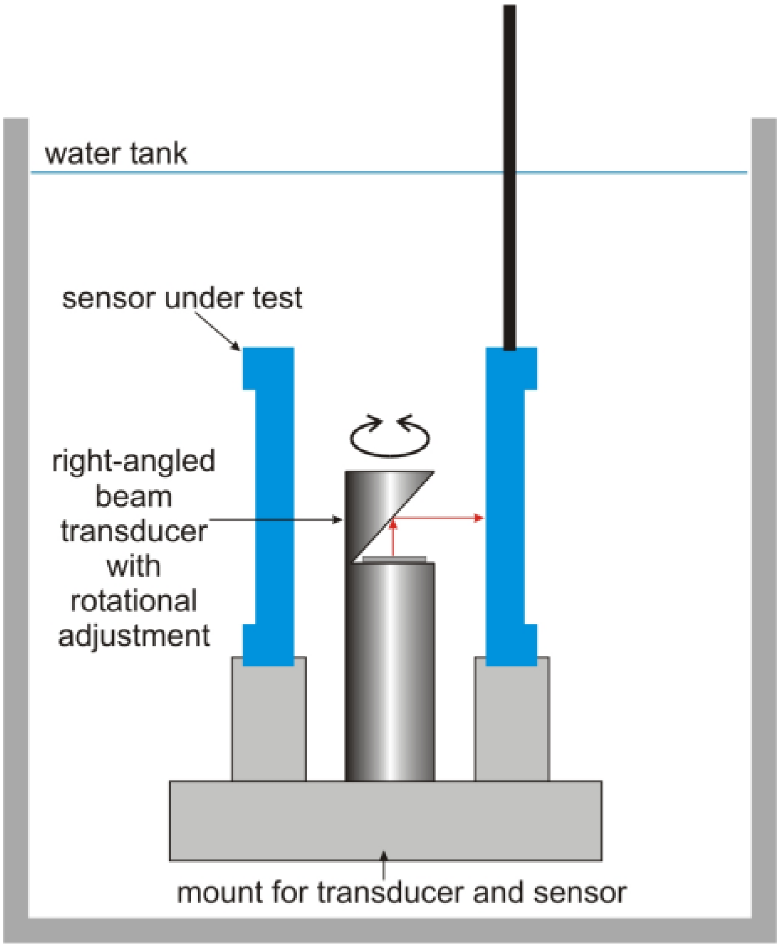


Figure 4.3: Schematic representation of sensor testing rig

The rig uses a 5 MHz Panametrics transducer, which has a 45 degree angled reflector attached to the transducer casing, such that the acoustic beam radiates at 90 degrees to the main axis of symmetry of the transducer. The transducer is small enough to be located inside the cavitation sensor, and so the response of the sensor to a short pulse of ultrasound incident on a specific region of its active surface can be investigated.

To ensure consistency, a test fixture was made to hold the transducer and sensor coaxially, and the sensor output was measured on an oscilloscope for three rotational positions (each at approximately 120 degrees separation) of the angled-beam transducer. The average of the peak-to-peak values derived from each waveform was recorded, and the procedure repeated for each sensor. Examples of two waveforms recorded 120 degrees apart (delayed in time for visualisation purposes) for sensor JIP 30_09 are shown in Figure 4.4.

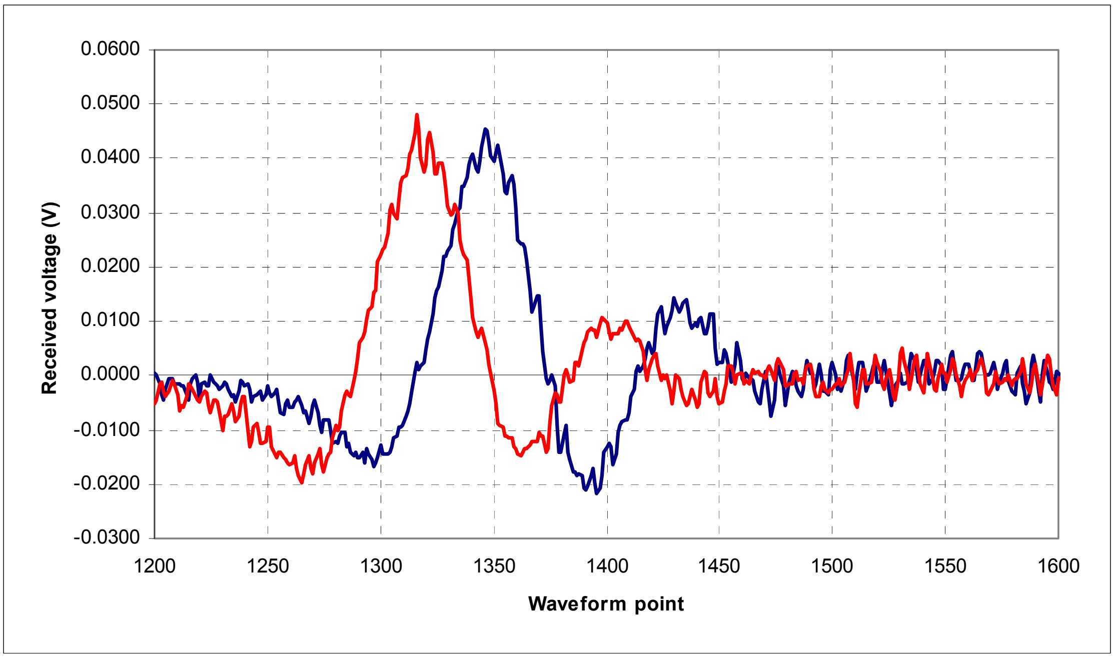


Figure 4.4: Two waveforms from sensor JIP 30_09, acquired during sensitivity tests

The results for the full sensor set are shown on Figure 4.5.

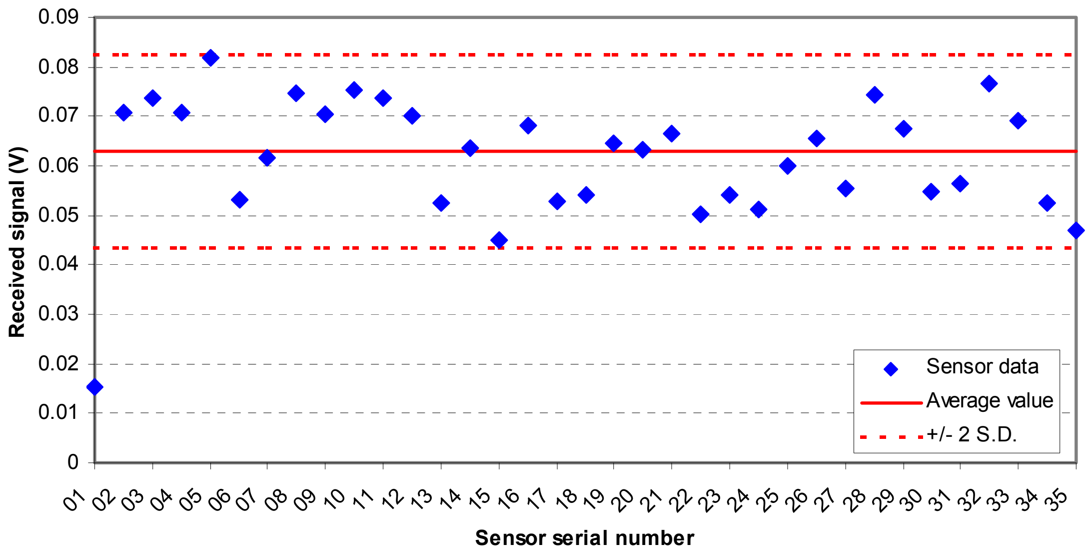


Figure 4.5: Sensitivity (defined as the average of the peak-to-peak voltages from 3 received waveforms) of each the 35 sensors manufactured during the project, alongside mean value and ±2 standard deviations for the full manufactured set (serial numbers 2-35)

Sensor JIP 30_01 can clearly be seen to deviate significantly from the general trend. Upon examination of the sensor, which had been used extensively in early acoustic tests, it was discovered that the sensor cable had been eroded by cavitation (see Figure 4.6), causing water ingress into the sensor itself. The sensor was cut open, and it was evident that the *pvdf* and absorber layers had completely delaminated, possibly due to water ingress down the cable, causing the very low sensitivity in comparison to the mean of the rest of the set. This serves to illustrate the erosive nature of the systems being characterised and the importance of ruggedising the sensors.

Figure 4.6: Cavitation erosion on cable from sensor JIP 30_01

It was noted above that the impedance measurements on Sensor JIP 30_25 indicated that it was outside ±2 standard deviations of the mean, but it is apparent from the acoustic tests that the sensor is functioning in line with the remainder of the batch, and so it was retained as part of the overall sensor set for full acoustic testing. In agreement with the electrical tests, the acoustic results over the full sensor set show the excellent manufacturing consistency achieved.

5 WP2 – MANUFACTURE OF FIVE COMPLETE SYSTEMS, COMPRISING CAVITATION SENSOR AND INTEGRATED ELECTRONICS

5.1 PRINCIPLES

The design concept for the signal processing electronics was based on experience of acoustic spectral features described in the literature that have been used by a variety of authors to describe cavitation activity. An example of a typical measured spectrum is shown in Figure 5.1. This was measured using a Brüel and Kjær 8103 hydrophone, located in an ultrasonic cleaning vessel operating at 40 kHz.

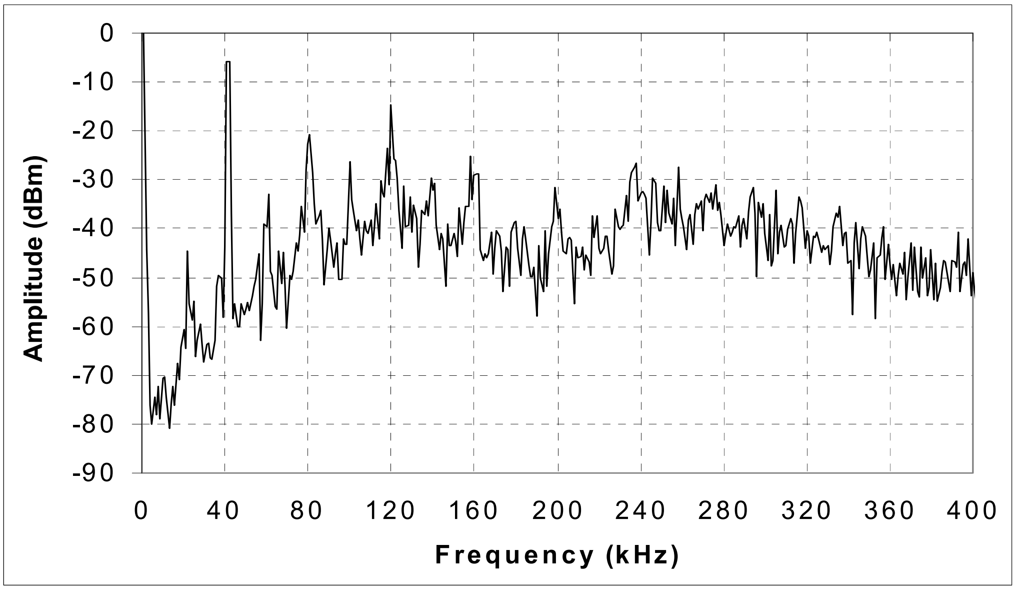


Figure 5.1: Typical acoustical spectrum received by an underwater acoustics hydrophone in a cavitating environment. The shape of the spectrum, with the 'dip' at 190 kHz, is attributable to the variation in the sensitivity response of the hydrophone.

It shows a range of signals:

- The fundamental frequency component, f_0, at approximately 40 kHz – in the main, this is produced by the direct driving field, with further contributions from linear bubble oscillations [6];
- Harmonics of the fundamental frequency component, at integer multiple frequencies of f_0 (80 kHz, 120 kHz and so on) – these are the result of nonlinear, stable bubble oscillations [7], acoustic signals that can be produced by the transducer itself due to harmonic signals in the electrical drive waveform, and possibly, nonlinear propagation occurring in the medium between the source and the receiver;
- Subharmonics of the fundamental, f_0/n, n is an integer; here the 20 kHz signal can clearly be seen – these have been interpreted as indicators of the onset of inertial cavitation activity [8], and can occur when a bubble of twice the resonant size is excited [9], or when a bubble takes greater than a single acoustic period to reach critical size prior to collapse [10, 11];

- Ultraharmonics of the fundamental, mf_0/p, where m and p are integers, $m > p$, and m/p is non-integral; signals can be seen at 60 kHz, 100 kHz and so on – these are bubble events of a similar type to those producing subharmonics [12];
- Broadband signal – the 'noise' at all frequencies, generated by the shock waves emitted upon bubble collapse, and by collapsing bubbles of a wide range of sizes [8].

The definitive work of Neppiras [13] indicated that the measurement of the broadband acoustic signal should enable some determination of the energy associated with inertial bubble collapse. Other authors have shown that this quantity can correlate with the effects of cavitation, such as degreasing [14] and surface erosion [15]. Neppiras suggested that in order to form a useful 'white-noise' probe, a device should possess a high frequency response, but also spatial sensitivity, which might be achieved through examining high frequency acoustic signals, where acoustic attenuation would restrict the propagation distance of emitted signals to perhaps a few cm. He considered that an acoustic source cavitating at kHz frequencies would produce broadband signals well into the MHz region, and so examining frequencies up to 20 MHz might be appropriate. Studies on a 40 kHz ultrasonic cleaning vessel have shown that there are components of the broadband signal up to, and beyond, 5 MHz, and so the MHz frequency ranges are used as an indicator of the level of cavitation power.

Thus, the specification for the Cavimeter signal processing electronics concentrated on the three of the signals listed above – the *fundamental* frequency, the *subharmonic* and the *broadband*. A schematic of the signal-processing route is shown in Figure 5.2.

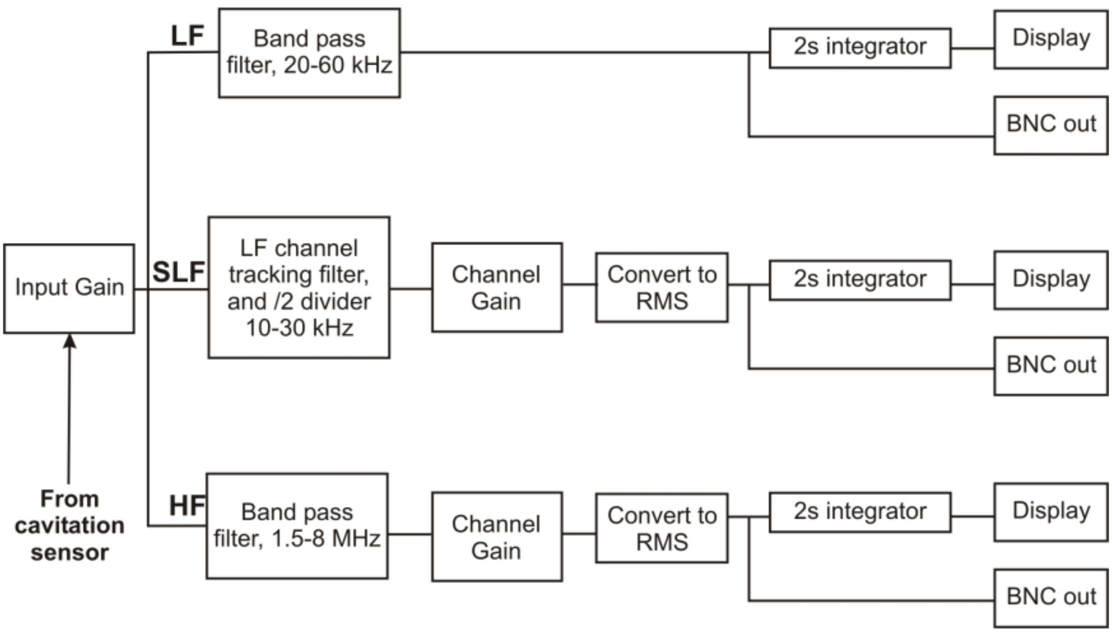


Figure 5.2: Schematic representation of signal processing unit

Following discussions to agree the specification, Kenelec (Middlesex, UK) built a breadboard prototype (see Figure 5.3), which allowed testing and feedback.

Figure 5.3: Breadboard prototype of Cavimeter

In particular, this prototype showed that:

- the input gain of the system was such that only the x0.1 and x0.2 settings could be used without the unit saturating, and so the overall input gain was reduced to increase the usable dynamic range;
- the initial concept of the broadband channel included a squaring circuit and this limited the useful dynamic range of the device, due in part to the specification of the numerical display, and so this was altered to be an RMS display in the final variant;
- the 'self zeroing' approach on the broadband channel resulted in an offset when the device was used at lower cavitation levels, and so would need to be improved upon or removed completely;
- the subharmonic and cavitation channel amplifier gains were tested using typical input signals, and the relative values adjusted, again to improve the useable range of the unit.

Following the initial tests, the final specification was agreed upon, and the build process for the five Cavimeters was embarked upon. The five completed Cavimeters were received in June 2006, serial numbers K0063, K0064, K0065, K0066 and K0067. These were tested electrically (see Section 6.2). The final system, shown with two cavitation sensors, can be seen in Figure 5.4.

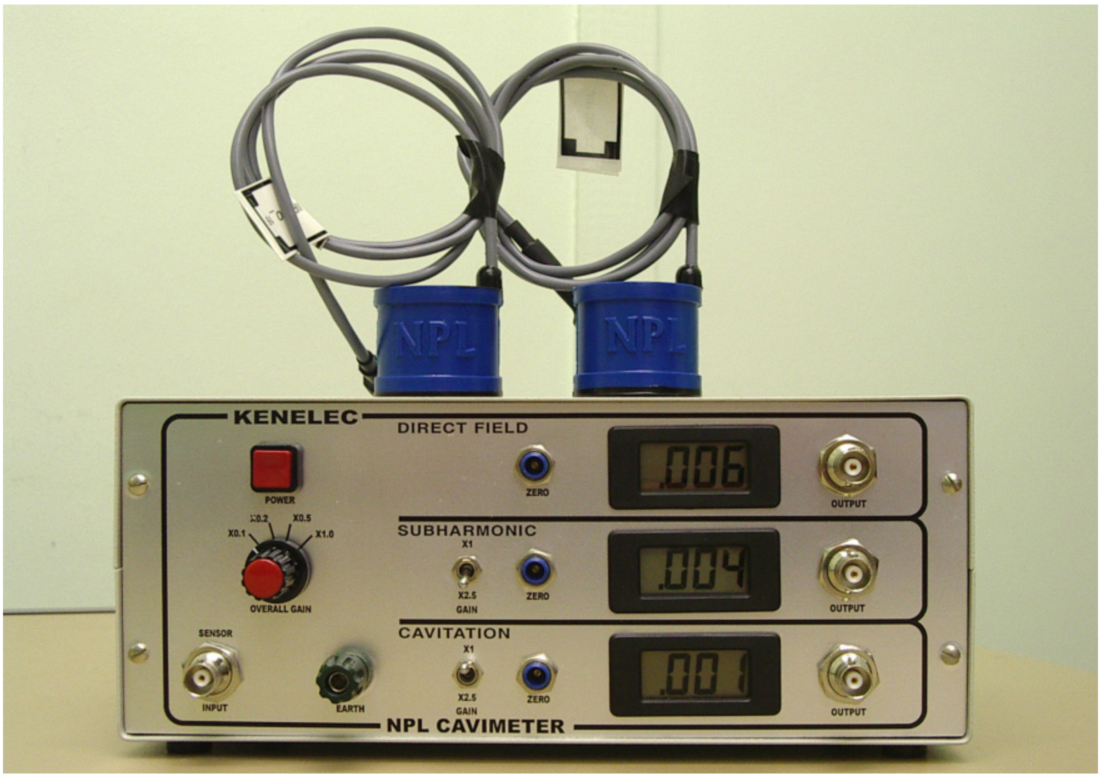


Figure 5.4: Final version of the Cavimeter and two cavitation sensors

5.2 SIGNAL-INJECT ELECTRICAL TESTING OF CAVIMETER UNIT REPONSE

A standard protocol was developed for carrying out the electrical tests on the units, and this is provided in Appendix B. The main investigations carried out are shown in Table 5.1.

Table 5.1: List of electrical signal inject tests carried out on the Cavimeter systems

TEST	DETAILS
1	Linearity of Low Frequency (LF) Channel (indicated reading), on all four Input Gain settings (1.0, 0.5, 0.2, 0.1) – Especially to look at issue of HF break-through
2	Linearity of LF Channel (indicated reading), determined on Overall Gain (OG)=x1.0 at frequencies of 20 kHz, 80 kHz & 120 kHz
3	Linearity of LF analogue output, determined on all four OG settings (1.0, 0.5, 0.2 & 0.1), at 40 kHz – looking at when & if the response starts to go non-linear
4	Demonstration of tracking of Subharmonic (SLF) channel – LF at 40 kHz, and frequency swept over range 19 kHz to 21 kHz
5	Linearity of SLF channel – LF = 40 kHz – single input voltage; OG = 1.0; linearity of SLF Channel determined at SLF channel Gain settings of x1.0 and x2.
6	Cavitation (HF) linearity of indicated reading with input HF Channel Gain setting; for following combinations (2 MHz; HF=1.0; 5 MHz; HF=1.0; 2 MHz; HF=2.5)
7	Linearity of analogue output for HF Channel, only at 2 MHz; HF=1.0 & all four OG settings (1.0, 0.5, 0.2 & 0.1)
8	Determine frequency dependent Gain of LF and HF Channels, for OG=1.0; HF=1.0
9	Input impedance determined over range 5 kHz to 150 kHz & 200 kHz – 12 MHz

A selection of the results obtained on each Cavimeter is shown in Figures 5.5-5.7, with the full data sets in Appendix B. Figure 5.5 shows the linearity of the Direct Field (DF) channel, in response to an input signal of frequency 40 kHz, and varying amplitude. Each Cavimeter exhibits a linear response up to the maximum input voltage (beyond which the DF display overloaded), and the agreement between the devices is generally very good, with the maximum difference in displayed signal level across the full applied range being 14%. Effort could have been spent in setting the systems up to generate more similar sensitivities, but in view of the need to progress the project, and similar differences in cavitation sensor sensitivities (see Figure 4.5) the degree of agreement was considered acceptable.

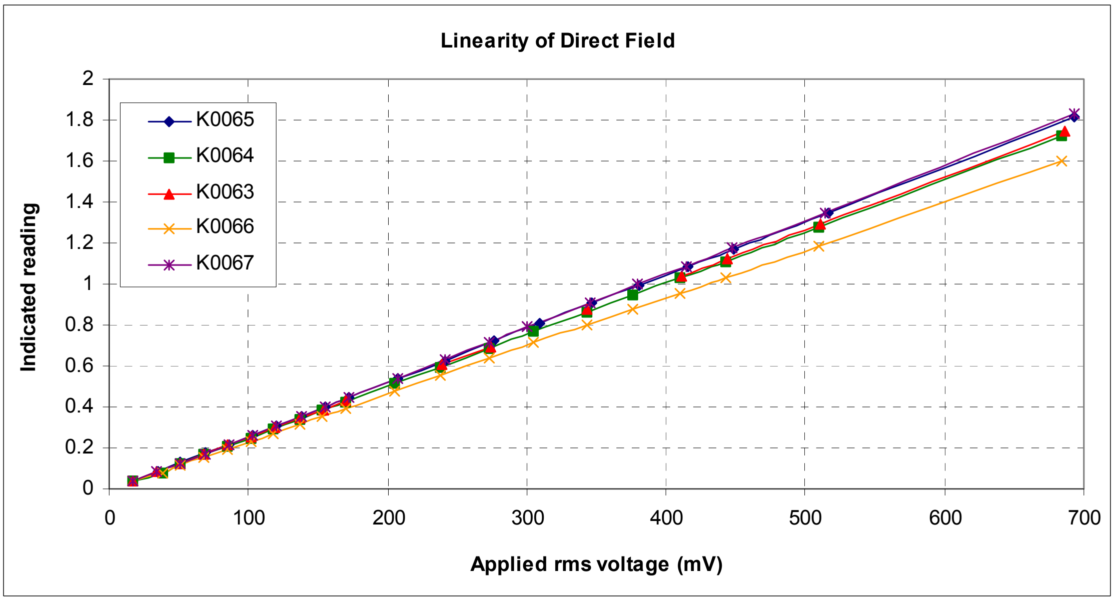


Figure 5.5: Variation in displayed DF signal level as a function of increasing input voltage, for the five Cavimeter units

Figure 5.6 shows the behaviour of the subharmonic channel. This test was carried out by applying a signal composed of two frequencies: a fixed level 40 kHz tone from one signal generator simulating the direct field (from which the subharmonic channel would obtain its 'reference' frequency), and a fixed level, swept frequency tone from a second generator. The response of the subharmonic channel as a function of the swept frequency is then shown for each device. Four of the devices exhibit a similar response, and K0064 and K0067 perform exactly as expected, with a well-defined peak corresponding to half of the 40 kHz simulated DF frequency. K0065 and K0066 perform in a similar manner, but demonstrate a peak at slightly below half of the DF frequency, although the peak width is sufficient to include the 20 kHz point at a good sensitivity.

The shape of the K0063 response is markedly different, with a very well-defined peak up to 20 kHz, but which extends to an overall –6 dB width of around 10 kHz (see Appendix B), in contrast to the 2-2.5 kHz bandwidth at the –6 dB level for the other Cavimeters. The reasons for this difference are unclear, and so it was decided that device K0063 would be retained at NPL, rather than being passed to the triallists. Further tests to diagnose and correct the response will be carried out in the near future.

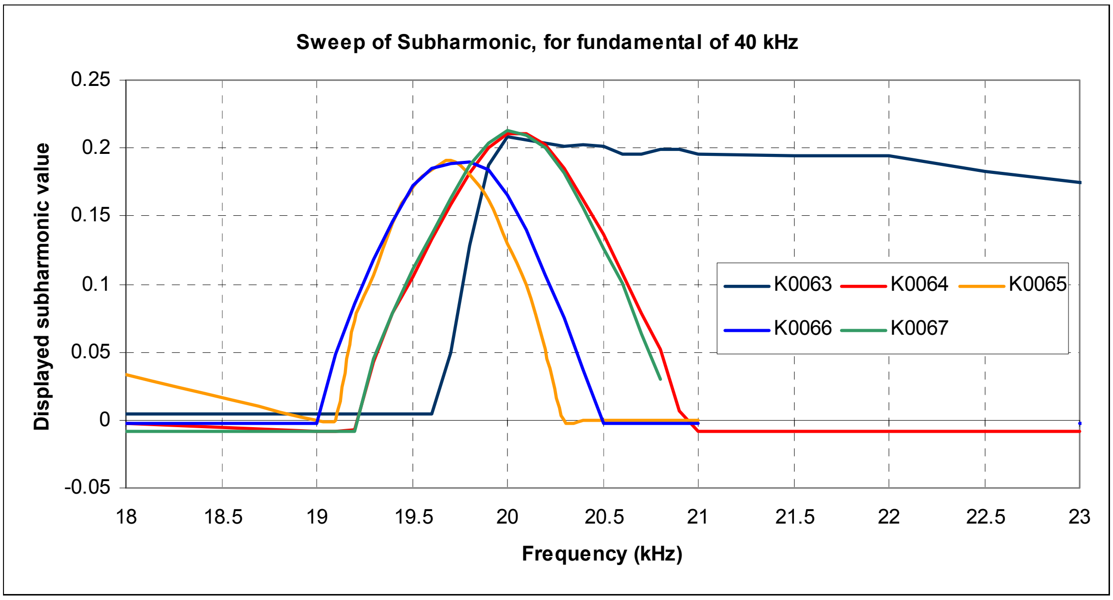


Figure 5.6: Variation in subharmonic channel signal level as a function of frequency, for the five Cavimeter units

Figure 5.7 shows the response of the Cavitation channel to a 2 MHz signal, produced by a signal generator and passed through an attenuator to obtain the sub-millivolt signals that mimic the low voltages produced by the cavitation sensor in the MHz range. The overall linearity of all devices is generally very good, although there is a deviation at the lower drive voltages. However, this is restricted to the lower end of the general operating range of the device, under single frequency testing, and so was not considered to be a major limitation for this project. Improving the low level performance will be the subject of further investigation.

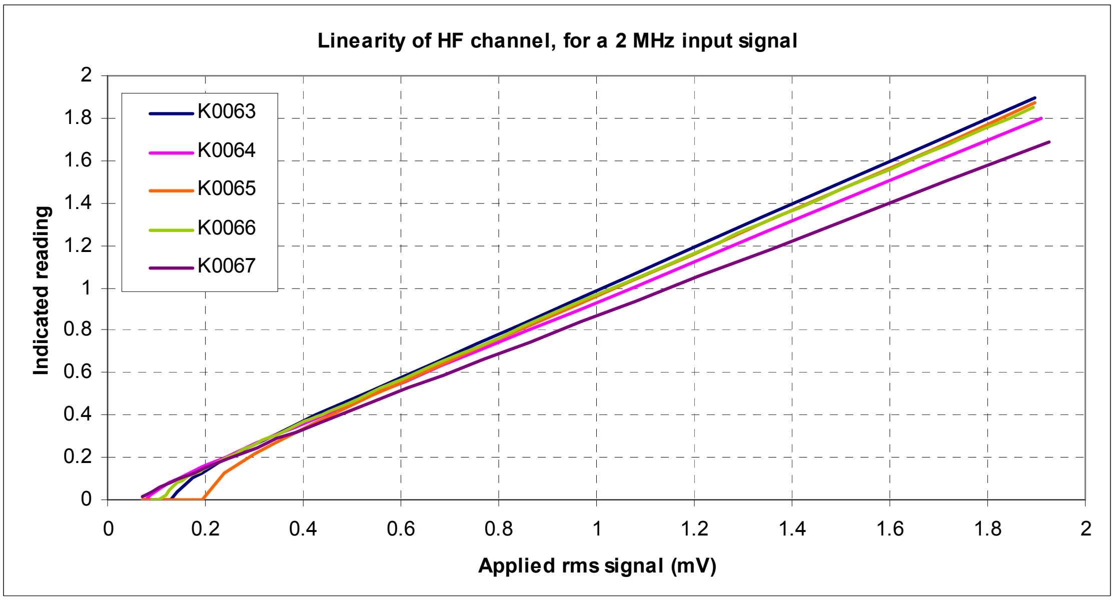


Figure 5.7: Variation in displayed Cavitation (HF) signal level as a function of increasing input voltage, for the five Cavimeter units

6 WP3 – TESTING OF CAVITATION SYSTEMS AT NPL

6.1 THE NPL REFERENCE CAVITATION FACILITY

The vessel established as the core of the facility is based on a model P1800-25 Ultrasonic Processing Cell, produced by Sonic Systems Ltd, (Somerset, UK). Figure 6.1 provides a schematic and a photograph of the reference vessel.

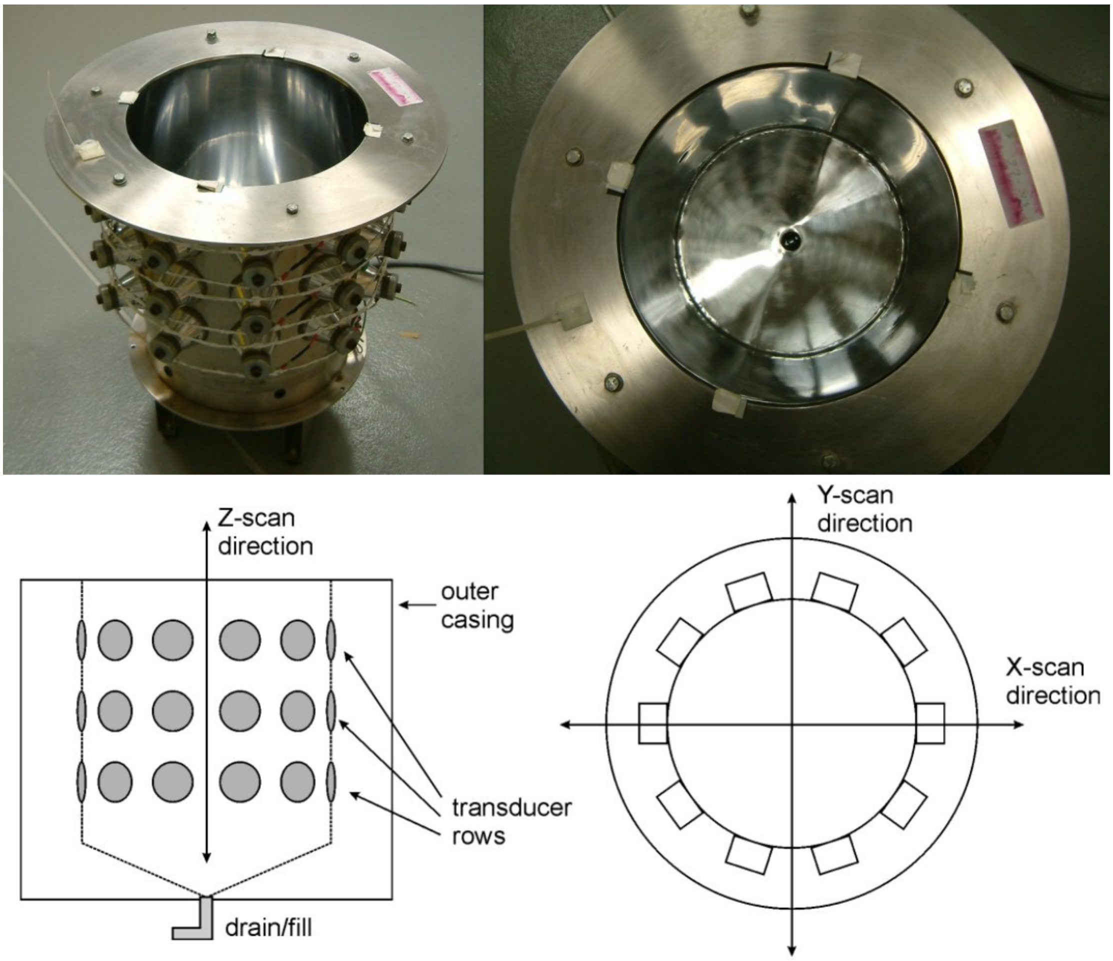


Figure 6.1: Reference cell schematic showing the 30 transducers deployed in three banks of 10 around its inner circumference, and photographs showing the vessel itself

Key features of the reference vessel are:

- Cylindrical profile: 330 mm high, internal diameter 312 mm, providing a volume of approximately 25 litres;
- 30 nominally identical 25 kHz PZT transducers, each 50 mm in diameter, epoxy-bonded to the vessel wall and radiating into the central volume, excited via 100%, 100 Hz modulation 25 kHz bursts;

- Transducers are distributed evenly in three horizontal rows of 10 devices, with the middle row positioned at the 'half height' position of the cylindrical part of the vessel;
- Three generators (one per row), supplying up to 600 W of electrical power each, so the maximum power density available is 72 W/l.

The reference vessel has a hard-chrome finished inner surface, to minimise the occurrence and effect of trapped air at the transmitting surface (thereby reducing cavitation erosion of the cell wall).

To evaluate the performance of the Cavimeters and sensors, a standard test protocol was adopted. Subsequent to the tests described in Section 4.3, in which the strongly uniform sensitivity of the full set of manufactured sensors was demonstrated, batches of five sensors were selected at random, and paired with a Cavimeter. For a given Cavimeter, each sensor was set up at the same nominal starting position in the vessel (centred in the X-Y plane and at a depth corresponding to the middle of the central transducer row, 187 mm), and scanned across the X-axis, using a central row drive level of 100 W. The RF output from the broadband analysis stage of the Cavimeter was connected to a Rohde and Schwarz RMS meter, and an average of four 1-second duration cavitation measurements taken at each position. The full available width (260 mm) was scanned, using a positional resolution of 2 mm. Figure 6.2 shows example results obtained for Cavimeter K0067 and five sensors, and the full range of tests carried out are shown in Appendix C.

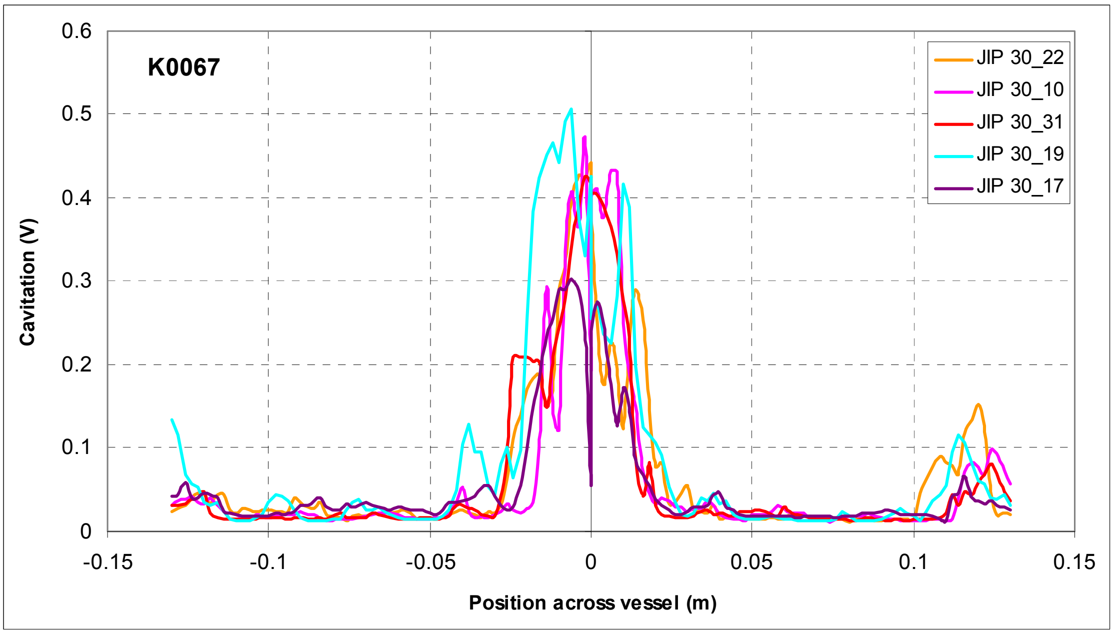


Figure 6.2: Cavitation activity X-axis scans across the reference vessel carried out using 5 sensors with Cavimeter K0067

The results show good general consistency across the vessel, with a strong peak shown at the centre, as would be expected from the focused configuration. The transducer at the positive X extreme in the vessel (positive x on the graph) is known to produce a marginally higher acoustic pressure than the corresponding transducer at the negative X extreme (16), and so the increase of cavitation activity seen by 4 of the sensors around the x=0.125m position is encouraging.

It is evident that several of the sensors tested illustrate a double peak in the vicinity of the centre of the vessel, and to investigate this further, higher resolution scans were carried out using a range of sensors over a more limited span. The measurements were carried out as above, but using an average of five 2-second duration cavitation measurements taken at each position. The results are shown in Figure 6.3.

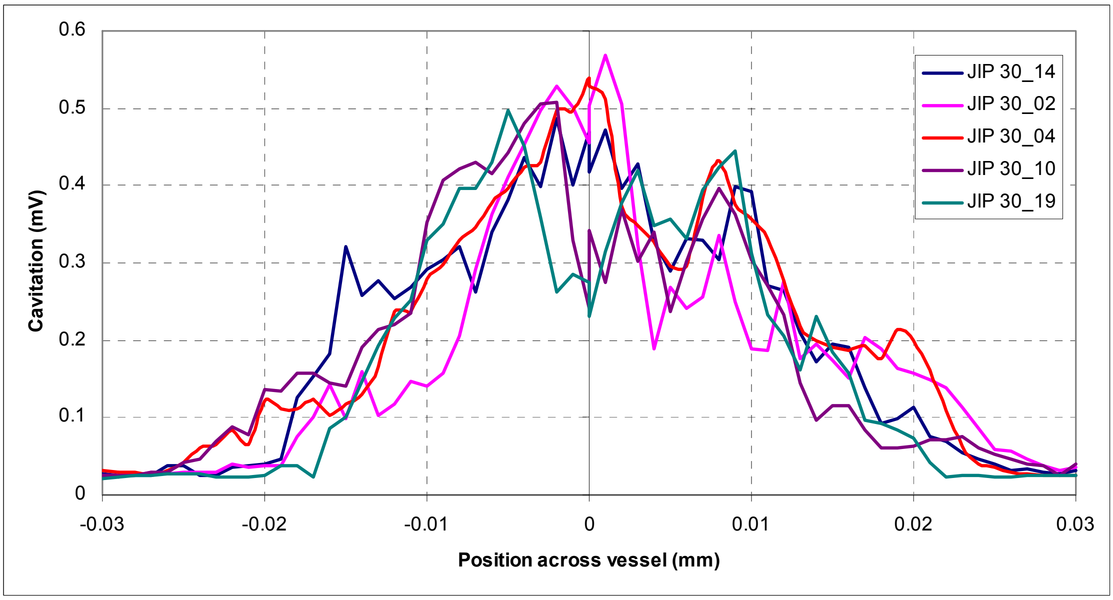


Figure 6.3: Cavitation activity x-axis scans across central region of reference vessel carried out using 5 sensors with Cavimeter K0067

The measurements over the central region of the vessel still show structure, but indicate that using a longer averaging time per measurement, and a larger number of measurements, lessens the double peak behaviour seen in Figure 6.2. This again suggests that there is greatest variation in the cavitation activity over the centre of the vessel, which would be expected. Also, the mounting configuration used for the sensors is subject to a certain degree of vibration, which causes variation in the actual location at which measurements are made. Improving this will be subject of future study, incorporating a revised mount constructed from carbon fibre to enhance rigidity.

7 WP4 – TRIALLING OF SYSTEMS BY COLLABORATORS

Following the successful testing programme for the Cavimeters and sensors at NPL, three UK triallists were contacted to arrange installation and demonstration visits. The Cavimeter and sensors were then used by the participants over a period of several months on their systems. Each triallist was then asked to complete a questionnaire to gather their views on the performance of the sensors and Cavimeter on a consistent basis. The questionnaire and a summary of their responses are contained here.

JIP Participant questionnaire

1. Describe the high power ultrasound systems on which the Cavimeter was used.

2. What measurements were made (e.g. cavitation at different power settings, positions, comparison with other techniques)?

3. What results were obtained (give example graphs/plots/photographs)?

4. What are your views on the following aspects of the Cavimeter:

   a) The ease of use and understanding of the system;

   b) The significance and relevance of the data it produces to your application;

   c) How the device could be improved;

   d) Where and how you think it could benefit your business area.

7.1 PARTICIPANT 1 - MANUFACTURER

1. Describe the high power ultrasound systems on which the Cavimeter was used.

The NPL Cavimeter has been evaluated on a range of ultrasonic cleaning vessels with liquid capacities ranging from 1.5 litres to 12 litres, typically with 1-4 transducers, operating in the range 20 – 50 kHz.

2. What measurements were made (e.g. cavitation at different power settings, positions, comparison with other techniques)?

The Cavimeter was utilised to conduct field mapping of ultrasonic vessels to give an indication of the homogeneity of the cavitation under 'no-load' conditions.

Distribution of the cavitating field and homogeneity of cleaning efficacy is of some importance to the company and the ultrasonic cleaning industry as a whole. Tests were performed by dividing a vertical plane within the vessel into a matrix of locations and taking the average of cavitation values for that location.

Tests were also performed to assess the impact of basket meshes on the cavitating field. Baskets are commonly used within the industry to carry contaminated items within the cleaning fluid. A comparison was made by examining the cavitation profile along the centre line of a vessel without a basket in place and then with a basket between the ultrasound source and the Cavimeter. Two types of basket were evaluated, one open mesh and the other a solid face with holes punched at regular spacing.

The effect of degassing on cavitational intensity has also been examined by examining the cavitational field at a location within a vessel run on degassed water. The strength of the field was monitored at various time intervals until the Cavimeter readout achieved a steady state (If indeed one was achieved).

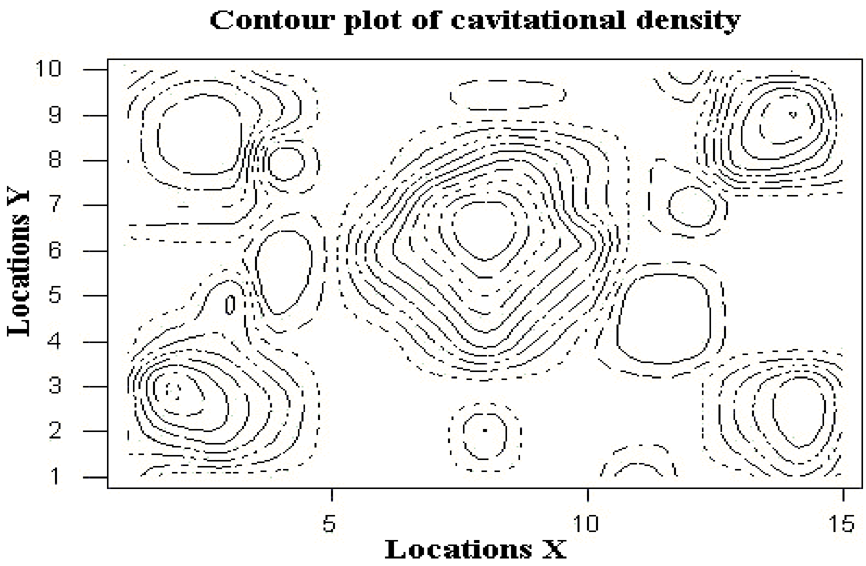
Comparison of the output of the Cavimeter has been made to foil test techniques and in house simulation of cavitating fields.

All tests were subject to an experimental protocol that maintained liquid depth, surfactant dosage, fluid temperature and length of degassing (where applicable).

3. What results were obtained (give example graphs/plots/photographs)?

The results noted below are an example of some of the exemplary data that has been gathered using the Cavimeter:

Figure (1) below shows the output of the cavitation sensor providing a contour map of the X-Y plane of a single transducer unit at $Z=2\lambda$. It can clearly be seen from the output that the cavitating field within the vessel is not homogenous and is subject to standing waves resulting from reflections from the tank geometry and water/air interface. This result was achieved with the open end of the receiver presented towards the radiating surface. Figure (2) shows a foil test taken along the same plane of measurement. Even with the disturbance to the cavitating field produced by the foil, it can clearly be seen that the Cavimeter produces a very close match.



Figure(1): Map of cavitational density within an ultrasonic cleaning vessel at Z=2λ

Figure (2): Foil erosion patterns due to cavitation.

The graph shown in figure (3) plots the results gained from the basket mesh test detailed above. It can clearly be seen from the results that although mesh 1 (open mesh wire basket) produced a small damping effect to the cavitation field, the difference was negligible and the overall pattern of cavitation was conserved. In comparison however, mesh 2 (consisting of regularly-spaced holes in a solid face) demonstrated a distinct lessening of cavitational activity and a large disruption to the cavitating field. The results of this simple experiment have large implications for the design and consumer choice of basket accessories for the ultrasonic cleaning industries.

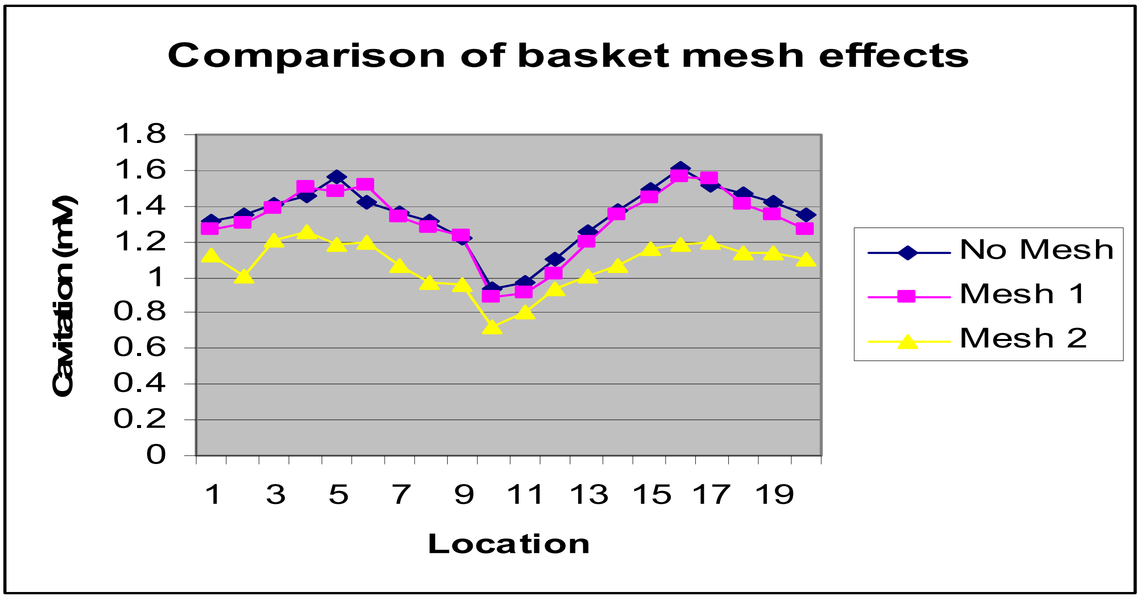


Figure (3): Plot of the effect of introducing and comparing basket mesh types.

The output of the cavimeter was also used to test the outputs of simulations. Figure (4) below shows an example of a simulated output of pressure against actual cavitational readings from the Cavimeter. Results were gathered from the Cavimeter with the sensor at 90 degrees to the radiating source to better detect the standing wave patterns along the centreline of the transducers.

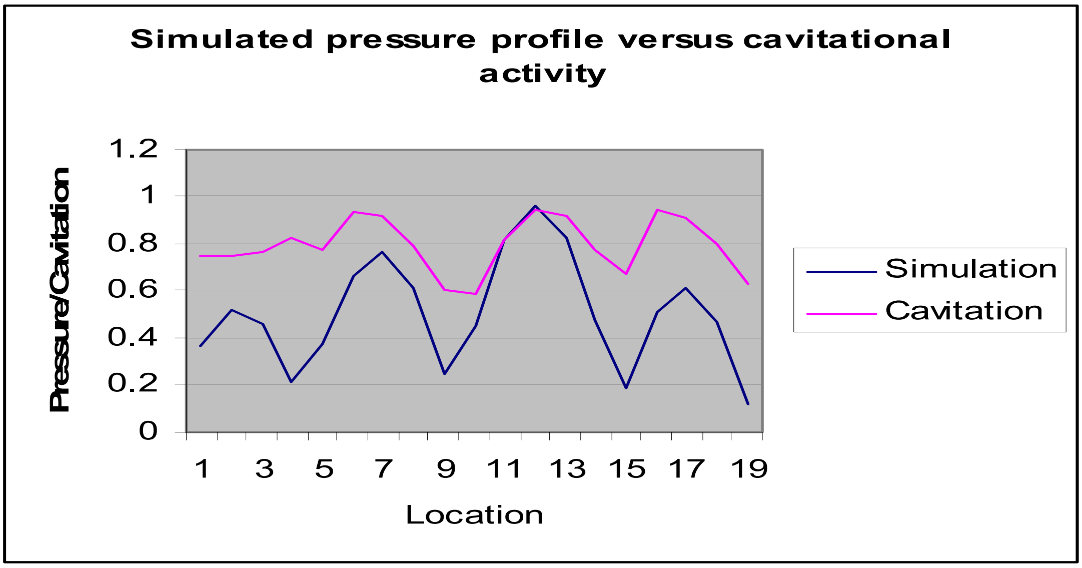


Figure 4: simulation versus Cavimeter output plot (note that pressure output from the simulation has been normalised for comparison purposes)

The measurement outputs achieved have helped confirm the link between a maximum pressure variation within the vessel and the onset of violent cavitation. The Cavimeter has also been used to help validate the simulation outputs, with model outputs and data showing a good level of correlation.

4. *What are your views on the following aspects of the Cavimeter:*

a) The ease of use and understanding of the system;

The short pamphlet accompanying the Cavimeter clearly and concisely covered the function of the meter, how it should be used and what each of the readouts signified. The Cavimeter was found to be easy to use and produced (in most instances) reliable/repeatable measurements over a range of tests and scenarios. The Cavimeter did however prove difficult to use in some circumstances due to the need to attach an earth braid between the input and the vessel to prevent inaccuracies due to noise.

b) The significance and relevance of the data it produces to your application;

The ability to easily and accurately measure cavitational field strength is of high importance to both the company and the ultrasonic cleaning industry. Without a standard method for assessing the impact of variables on the ultrasonic cleaning process, it is extremely difficult to make improvements or statements on optimum conditions for cavitation. The case shown in question 3 (fig 3) of the varying basket mesh designs gives a prime example of how significant a quantitative representation of cavitation is to the business.

Providing a reliable standard measurement method of cavitation measurement may also in future provide a means of cross comparing various ultrasonic cleaning systems and technologies thus allowing a reasoned selection to be made between competing systems rather than, as is the case at present, end users having to make a choice based on marketing spiel and technological truisms.

c) How the device could be improved;

Although the Cavimeter has been found to be far more stable and produce a more relevant set of results than most systems tested, the following recommendations are put forward (in no particular order):

- The use of the earth braid between the receiver input and the tank vessel is clumsy and inconvenient. Loosing contact between the vessel and the earth braid seriously de-stabilises results. A future design should look at a better way to improve noise elimination.
- Although smaller than some alleged cavitation meters commercially available, the diameter and height of the NPL probe section makes it a little inconvenient for some measurements and difficult to improve accuracy in full field mapping. If possible a smaller probe end/housing would be desirable thus allowing better coverage of areas.
- From a researcher's point of view, the relations between direct field, cavitation and the sub harmonic are all very interesting and useful, but possibly from an end users perspective only the cavitation field strength would be relevant with other readouts confusing matters?
- Following from the above comment, from an industrial point of view the case housing the electronics is too large. Ideally a handheld, portable system would be ideal for most end users.

- The ability to electronically store values at a location and 'dump' the memory to a PC would be highly desirable.
- Defining a standard unit for cavitation and expanding the operating range of the electronics (without having to resort to manually adjusting the gain) would also be highly desirable. Possibly being able to tie in the cavitation field strength to a proven cleaning capability would also be useful.

d) Where and how you think it could benefit your business area.

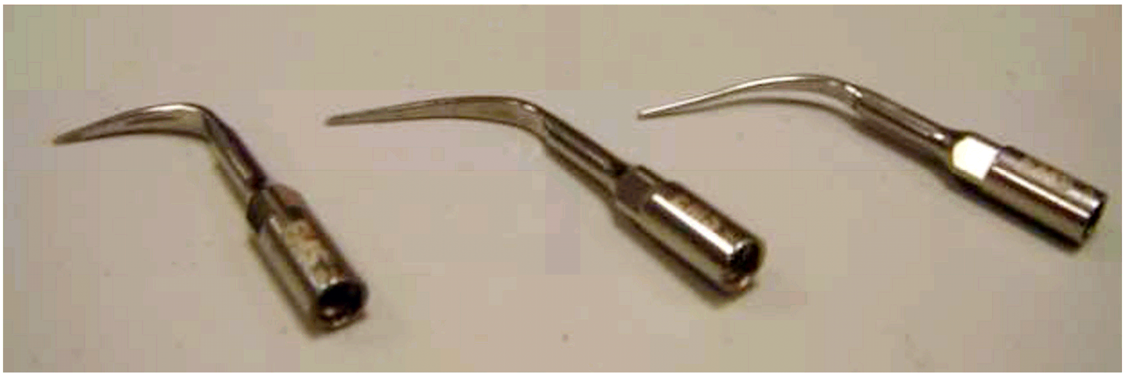
As has already been shown, the Cavimeter could be of immense benefit when assessing the variation of variables upon the ultrasonic process. There are also implications for maintenance and validation of ultrasonic units, with the Cavimeter capable of detecting variation in field strength and malfunctioning transducers. This ability to compare and diagnose cavitating fields may prove useful in part fulfilment of HTM2030's validation requirements for ultrasonic cleaners used in medical/dental settings.

Also a recognised, standard method of cavitation measurement would lead to more informed decisions by companies and end users when selecting ultrasonic technologies, leading to increased confidence in the ultrasonic cleaning technologies.

7.2 PARTICIPANT 2 – RESEARCHER

1. *Describe the high power ultrasound systems on which the Cavimeter was used.*

Commercially-available dental (de)scaling unit with 10 power settings operating at a frequency in the approximate range 20-40 kHz. The tips (shown below) are 1-3 mm in width.

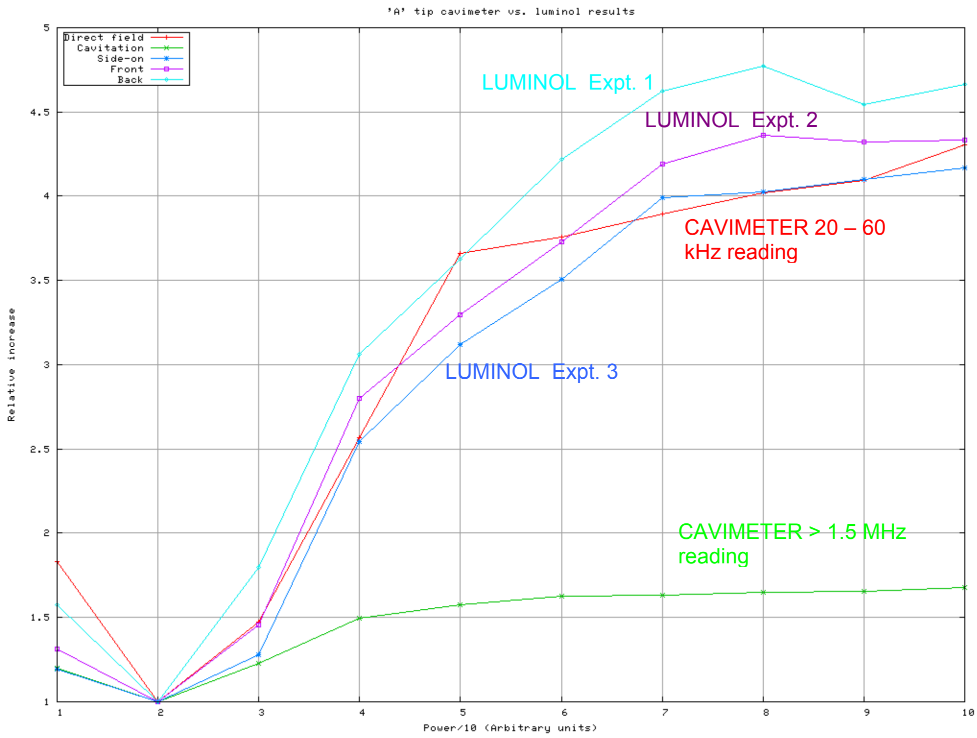


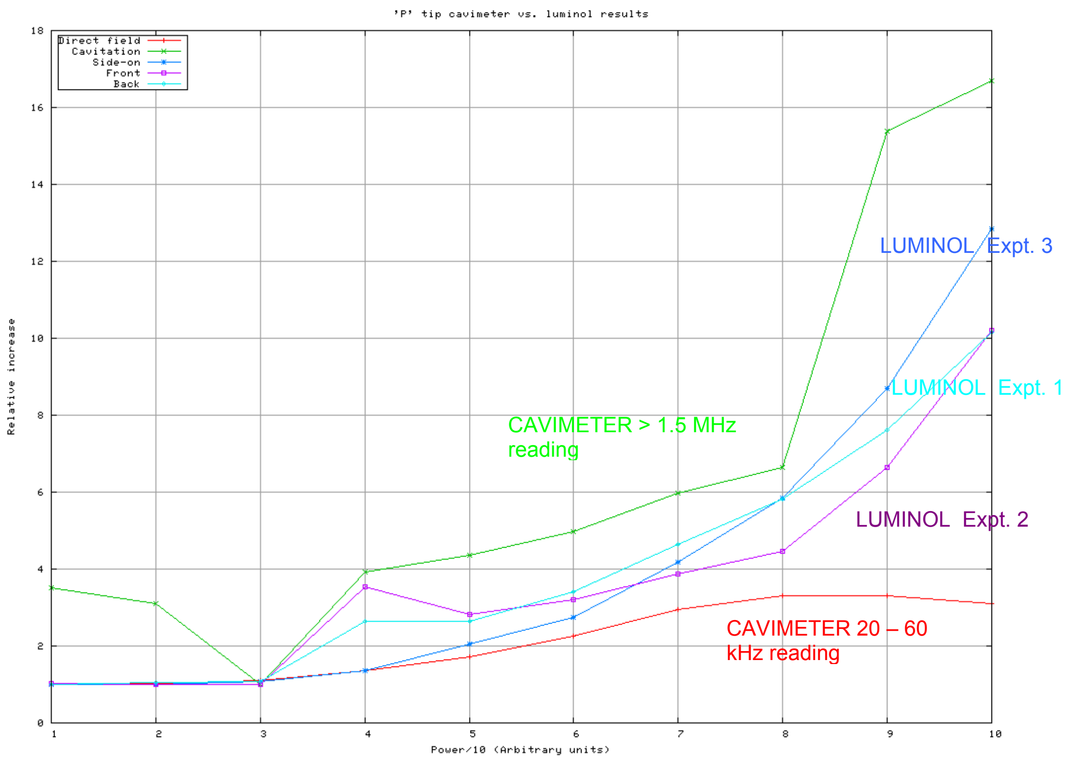
2. *What measurements were made (e.g. cavitation at different power settings, positions, comparison with other techniques)?*

Immersion of three different designs of dental scaler tip in distilled water inside the cylindrical sensor. All power settings were monitored and compared with measurements from light emission from luminol (a measure of the concentration of hydroxyl free radicals formed) intensity measurements.

3. *What results were obtained (give example graphs/plots/photographs)?*

See graphs/data included below. The correlation with chemical measures of ultrasound was pleasing.





4. *What are your views on the following aspects of the Cavimeter:*

a) The ease of use and understanding of the system;

Brief yet informative user notes were sufficient to understand how to operate the instrument.

b) The significance and relevance of the data it produces to your applications and research areas;

A further technique, in addition to the luminol luminescence studies and HTA fluorescence studies, for monitoring cavitation output from dental scalers. The real-time monitoring capability of the JIP device has already shown fluctuating output power of the dental scaler used in the study. The readout is of limited interpreted use but does give indications of temporal stability and change in output.

c) How the device could be improved;

Allow selection of integration time for measurements (to cope with fluctuating output power). Possibly allow more control over gain.

d) Where and how you think it could benefit your research areas.

As a possibly more-sensitive monitor of cavitation in solution. Development of the subharmonic channel to use as a sensor for the onset of transient cavitation is potentially very useful in our research on the cleaning efficiency of dental scalers.

7.3 PARTICIPANT 3 - MANUFACTURER

Participant 3 provided a comprehensive report, including results from studies carried out on two separate systems. System 1 was a multi-transducer vessel operating at 20 kHz. The cavitation sensor and Cavimeter were used to evaluate the cavitation activity at a number of vessel locations, and comparisons were made with domestic-grade aluminium foil, mounted on a wire frame. Measurements in the centre of the vessel showed that the cavitation activity level generally decreased when the power input to the vessel was increased, and the corresponding foil erosion patterns were also less prominent at higher power settings; but at the vessel walls, higher activity and erosion levels were seen when the power input was increased. This suggests that the cavitation shielding (in which using vessels at high output levels can generate a 'scattering' layer of bubbles close to the output face of the transducer under test) was occurring.

However for some measurements using a greater number of transducers, the extent of foil erosion increased with higher input powers, yet the cavitation activity decreased. It is possible that this was due to insufficient sensor wetting, or difficulties in repeating sensor locations in the vessel, but required further study[1].

System 2 was a single transducer vessel, again driven at 20 kHz, in amplitude-modulated mode. Figure 1 shows the results obtained for cavitation activity and direct field by varying the drive power, with the sensor located at the vessel centre.

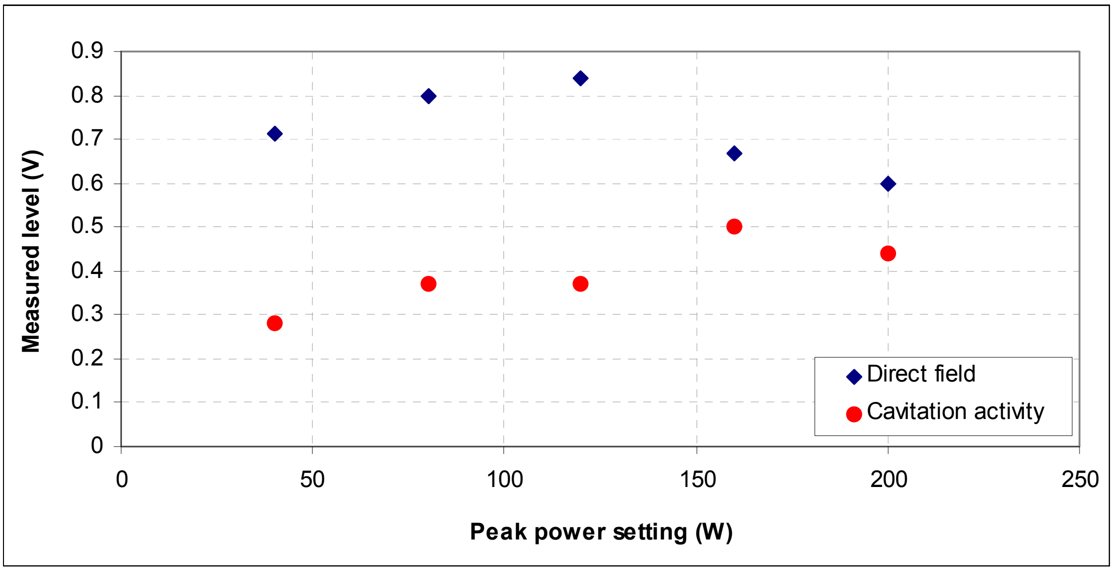


Figure 1 – Progression of Cavimeter LF and HF channels with applied power

These suggest the likelihood of cavitation shielding again, with a slow decrease in the Direct Field following an initial rise, but a longer-lasting increase in the cavitation activity. Comparison measurements were also made using aluminium foil coupons, shown in Figure 2.

[1] Further measurements were carried out during a separate visit to Participant 3, and these resulted in improved results (see Section 7.4)

Figure 2 – Erosion tests made with and without sensor in vessel

The lower set of foil samples demonstrate less erosion, and suggest that the sensor causes a reduction in the vessel output, in some way 'loading' the system mechanically.

Participant 3 concluded their report with a series of recommendations, as follows:

- The Cavimeter time response should be reduced, perhaps down to a second;
- A two digit readout would suffice;
- The inability to use the sensor in solvents and acids would seriously limit its use in a wider industrial field and should be addressed;
- If it is the case that the sensor interferes with the vessel then that would cause problems. Could some thought be given to adding a smaller sensor to the range?

7.4 TRIALLIST FEEDBACK SUMMARY

Two of the three participants found the sensor and Cavimeter gave good correlations with existing cavitation monitoring methods (optical, chemical and erosive), which is encouraging, and following a visit to the third participant, further measurements were carried out that demonstrated better agreement with existing techniques than had been seen initially. Observations on the usefulness of the device from all participants included:

- The Cavimeter was found to be easy to use and produced (in most instances) reliable/repeatable measurements over a range of tests and scenarios;
- The ability to easily and accurately measure cavitational field strength is of high importance to both the company and the ultrasonic cleaning industry;
- Providing a reliable standard measurement method of cavitation measurement may also in future provide a means of cross comparing various ultrasonic cleaning systems and technologies.

Users felt that the Cavimeter could be improved in the following ways:

- Allow selection of integration time for measurements (to cope with fluctuating output power), and possibly allow more control over gain;
- Development of the subharmonic channel to use as a sensor for the onset of transient cavitation is potentially very useful in our research;
- The use of the earth braid between the receiver input and the tank vessel is clumsy and inconvenient. Losing contact between the vessel and the earth braid seriously de-stabilises results. A future design should look at a **better way to improve noise elimination**;
- Although smaller than some alleged cavitation meters commercially available, the diameter and height of the NPL probe section makes it a little inconvenient for some measurements and difficult to improve accuracy in full field mapping. If possible a **smaller probe** end/housing would be desirable thus allowing better coverage of areas;
- The ability to electronically store values at a location and 'dump' the memory to a PC would be highly desirable;
- **Defining a standard unit for cavitation** and expanding the operating range of the electronics (without having to resort to manually adjusting the gain) would also be highly desirable. Possibly being able to tie in the cavitation field strength to a proven cleaning capability would also be useful;
- The current inability to use the sensor in solvents seriously limits its use in a wider industrial field, and should be addressed.

The three areas highlighted in bold represent important areas for investigation, and will be the subject of future research at NPL.

8 PROJECT ACHIEVEMENTS AND CONCLUSIONS

The strong collaborative nature of the project has meant that significant technical advances have been made, particularly in the manufacture of a batch of 35 cavitation sensors of stable performance. The improvements to the sensor design and development of a repeatable manufacturing process, in terms of ruggedness and the ability to produce sensors in small batches are evidenced by the data shown in Figures 4.5 and 6.3, demonstrating the excellent manufacturing repeatability and performance achievable. The development of the 5 signal processing Cavimeters also represents a significant technical achievement.

From electrical and acoustical testing, the comparative sensitivity of the 35 sensors was excellent, with the sensitivity of all intact devices falling within two standard deviations of the mean. When tested in a cavitating environment, the randomly-chosen batches of sensors and Cavimeters generally showed repeatable and stable performance, with just two sensors falling only slightly below expectations.

The subsequent trialling exercise provided the opportunity for three manufacturers and researchers across a range of application areas to trial a unique new NPL measurement capability, and gave valuable feedback on the utility of the developed sensor and electronics and how the systems might be improved to better meet the requirements of industry. Further, it has started to shape the longer-term thoughts of manufacturers about their future measurement requirements, and as a consequence, collaborations should take place in the forthcoming 2007-2010 NMS Acoustical Metrology Programme towards developing a standard parameter for cavitation measurement. Further NMS work should also develop solutions to the problems of electrical noise immunity and physical sensor size noted by the trialling participants. Additionally, the existing Cavimeters are intended to be used in a second trialling exercise with other interested parties as part of the next NMS Programme.

The early stages of the JIP were also presented at the 2006 Ultrasonics Industry Association Symposium in San Diego, which improved worldwide awareness of NPL's work in cavitation detection.

The intention is now to develop the Cavimeter and sensors into a full commercial product, and to this end, discussions are now underway to design and manufacture a new version of the Cavimeter that incorporates some of the design improvements recommended by the triallists, and to test this at NPL. Once completed, the intention is then proceed to commercial production and distribution, for which a manufacturing partner will be required.

9 ACKNOWLEDGEMENTS

The authors acknowledge the financial support of the Measurements for Innovators Joint Industrial Project scheme, funded by the UK Department of Innovation, Universities and Skills, and the in-kind contributions of time, expertise and access to facilities provided by the triallists.

This report is dedicated to Harvey Thompson.

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APPENDIX A

Industrial trialling of a novel sensor providing objective measurements of the effectiveness of high power ultrasonic equipment

SUMMARY

This project involves the industrial trialling of a new sensor and electronics module that will provide objective measurements of the effectiveness of high power ultrasound processes, allowing them to be reliably monitored, controlled and optimised. Despite the widespread use of high power ultrasound within industry (the world-wide market for ultrasonic cleaning systems alone is in excess of $4 billion), there remains no accepted method for measuring or monitoring the degree of acoustic cavitation occurring with a process. Acoustic cavitation is the oscillation of small bubbles within the liquid medium, whose violent collapse gives rise to the extreme physical and chemical changes which drive forward the industrial process.

The project aim is to manufacture five cavitation sensor units (including bespoke electronics) and to trial these within industrially relevant environments, provided by a sample of UK equipment manufacturers. Knowledge gained from this trialling will feed into an improved understanding of the factors affecting cavitation sensor performance.

OBJECTIVES

Three main objectives of the project are to :-

- manufacture five cavitation sensor – electronic module units which may be considered pre-production systems;

- complete industrial trialling of the units, in a range of applications, providing an objective assessment of the performance of the sensors;

- collate and critically analyse the trialling results, feeding knowledge gained back into an improved specification of the cavitation sensor, significantly shortening time-to-market.

THE NOVEL CAVITATION SENSOR

Oscillating and collapsing bubbles undergoing acoustic cavitation emit sound waves. The novel sensor considered in this project, developed as part of a NPL Strategic Research (SR)* project, detects these acoustic signals. Their special features are a wide measurement bandwidth (they are able to monitor signals up to 10 MHz) and spatial sensitivity, both of which are critical to reliably characterise cavitation. Sensor proof-of-principle has been demonstrated through both SR and NMSD unit programme funding, but only for a limited number of experimental conditions, with the sensors having been developed through to prototype stage. NPL owns the IPR relating to the cavitation sensor (Patents have been granted in the UK, Germany, Japan and the US).

* The novelty and potential industrial impact of the sensor was acknowledged when a paper describing its concept and proof-of-principle won the IEEE, Ultrasonics, Ferro-electrics and Frequency Control (UFFC) outstanding paper award for 2003.

The commonly used test applied by manufacturers and required by NHS Standards for cleaning medical instruments, is to immerse a thin layer of aluminium foil in the vessel of interest. Cavitation bubble collapse, occurring close to the foil surface, leads to holes being punched in the foil, and assessing the extent of eroded material provides a purely qualitative observation of whether cavitation is occurring. However, whilst useful, it has been impossible to standardise this test into an accepted objective method. Recent work carried at NPL (3) has demonstrated that the cavitation sensor provides a characterisation capability which correlates well with aluminium foil results, indicating the sensor output relates closely to the effectiveness of the process. This strongly suggests that the novel sensor will provide the basis of a standardised method of measurement.

BENEFICIARIES

This project will provide partners with access to a completely new measurement capability, bringing a range of benefits to the manufacturer who will then be able to optimise the application of acoustic cavitation within high power applications, for example:-

• allowing them to quantitatively investigate the spatial distribution of cavitation (something that cannot be reliably carried out now), enabling them to optimize system design and operation to ensure cavitation activity is made as uniform as possible;

Note: The existence of 'hot-spots' and 'cold-spots' in cavitation activity is a universal problem for these systems which in some applications, for example the cleaning of surgical instruments, can have important safety implications – in some areas of the vessel, instruments will not be cleaned at all.

• with access to this measurement capability, the quality and performance of equipment will improve, providing UK manufacturers and users with a technical edge;

• manufacturers will be able to investigate different liquid media, ensuring that environmental friendly chemicals are used which do not result in any degradation in cleaning performance;

• for companies involved in sonochemical (very high acoustic energy) processing, the sensor will additionally provide fundamental information, making scale-up to the industrial level more reliable.

• following sensor trialling and the demonstration of its capabilities, the objective will be to feed back this information into a refinement of its design (and that of the associated electronics), allowing it to be commercialised;

• progress within the High Power Ultrasound - Cavitation work being carried out under the 2004 - 2007 NMS Acoustical Metrology programme will be greatly accelerated, through a much improved understanding of the factors affecting sensor performance and its response when used under various conditions. The services which NPL will provide to industry, related to cavitation assessment, will be much quicker in coming on-stream, accelerating the benefit to UK industry.

WORKPLAN

The project will produce five sensor-electronics systems, each including a specially built compact electronics module, making the system easier and faster to apply for industry, thereby greatly increasing information gathered. Trialling will be carried out in parallel, once the sensor-electronics systems have been manufactured and tested by NPL.

Note: the electrical signal levels produced by the cavitation sensors are small, and special electronics modules have to be built to amplify and filter the signal, allowing the important characteristics to be extracted and presented in a readily usable form.

The project will be executed in five Work Packages, whose phasing is described schematically in the Gantt chart in Figure A.1.

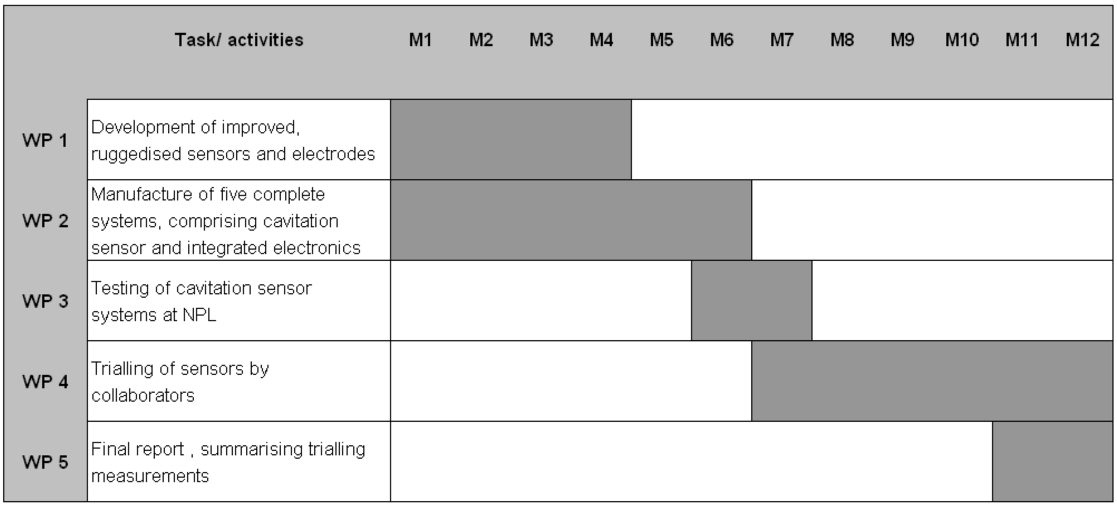


Figure A.1: Schematic representation of the scheduling of the various Work Packages within the proposed 12 month project. Months are labelled M1, M2 etc.

WP1 Development of improved, ruggedised cavitation sensors and electrodes – 4 months

WP2 Manufacture of five complete systems, comprising cavitation sensor and integrated electronics* - 6 months

WP3 Testing of cavitation sensor systems at NPL - 7 months

WP4 Trialling of cavitation sensors by collaborators - 11 months

WP5 Final report, summarising trialling measurements - 12 months

* the fifth cavitation sensor system will act as a back-up for the industrial triallists, but will also be in use at NPL during the trial period, enabling valuable additional data to be acquired.

DELIVERABLES

There are two major Deliverables which will be generated by the project:

Report detailing cavitation sensor trialling measurements carried out in a range of high power acoustic fields.

Note: although beyond the time-scale of the current project, the technical knowledge of the sensor performance and capability embodied in the Report will be fed into the standardisation arena through International Electrotechnical Committee (IEC) TC 87 WG3 "High power transducers". WG3 is currently considering ways of standardising the performance of ultrasonic cleaning systems. An NPL member of staff has responsibility for a project to develop a standard for characterising these systems, making NPL ideally positioned to ensure benefits from the proposed project are fully exploited.

Five cavitation sensor – electronic module systems.

Note: The project will attract considerable interest from other manufacturers and users (there are 25 – 30 manufacturers of ultrasonic cleaning equipment in the UK), but, with the need to ensure the project is completed over a reasonable time-scale, the number involved will necessarily be limited. To widen the impact of the project, following its completion, the manufactured cavitation detector units will be made more widely available for short-term loan/demonstration purposes. As part of the 2004 – 2007 Acoustical Metrology Programme, a web-site describing the high power work at NPL will be initiated, and this will be used as a vehicle for publicising the current project.

RISK

Whilst the manufacture of robust electrodes able to withstand the hostile environment requires the solution of a number of technical issues, on the basis of previous work, risks associated with this are manageable. Undoubtedly, the major issue within the project will be the commercial sensitivity perceived by some of the companies (particularly in the cleaning area) regarding how data generated within the project is used. Ways of addressing this will be agreed by NPL with the individual partners, and this might involve only NPL having access to all measurement results and through the signing of non-disclosure agreements. The key will be to emphasise that the project centres on *trialling the performance of the cavitation sensor*, rather than *comparing relative capabilities of equipment fabricated by different manufacturers*. Any report disseminating the results of the project to a wider audience will have to maintain manufacturer anonymity.

APPENDIX B SUMMARY OF ELECTRICAL TESTS CARRIED OUT ON CAVIMETER MODULES

The tests carried out are shown in Table B.1.

Table B.1: Electrical testing programme for Cavimeters

TEST	DETAILS
1	Linearity of Low Frequency (LF) Channel (indicated reading), on all four Input Gain settings (1.0, 0.5, 0.2, 0.1) – Especially to look at issue of HF break-through
2	Linearity of LF Channel (indicated reading), determined on Overall Gain (OG)=x1.0 at frequencies of 20 kHz, 80 kHz & 120 kHz
3	Linearity of LF analogue output, determined on all four OG settings (1.0, 0.5, 0.2 & 0.1), at 40 kHz – looking at when & if the response starts to go non-linear
4	Demonstration of tracking of Subharmonic (SLF) channel – LF at 40 kHz, and frequency swept over range 19 kHz to 21 kHz
5	Linearity of SLF channel – LF = 40 kHz – single input voltage; OG = 1.0; linearity of SLF Channel determined at SLF channel Gain settings of x1.0 and x2.
6	Cavitation (HF) linearity of indicated reading with input HF Channel Gain setting; for following combinations (2 MHz; HF=1.0; 5 MHz; HF=1.0; 2 MHz; HF=2.5)
7	Linearity of analogue output for HF Channel, only at 2 MHz; HF=1.0 & all four OG settings (1.0, 0.5, 0.2 & 0.1)
8	Determine frequency dependent Gain of LF and HF Channels, for OG=1.0; HF=1.0
9	Input impedance determined over range 5 kHz to 150 kHz & 200 kHz – 12 MHz

For each Cavimeter, electrical tests were carried out using the equipment depicted in Figure B.1.

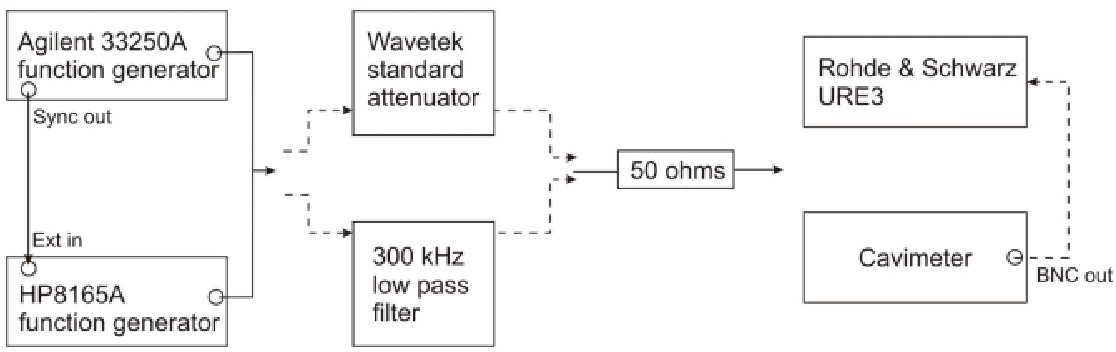
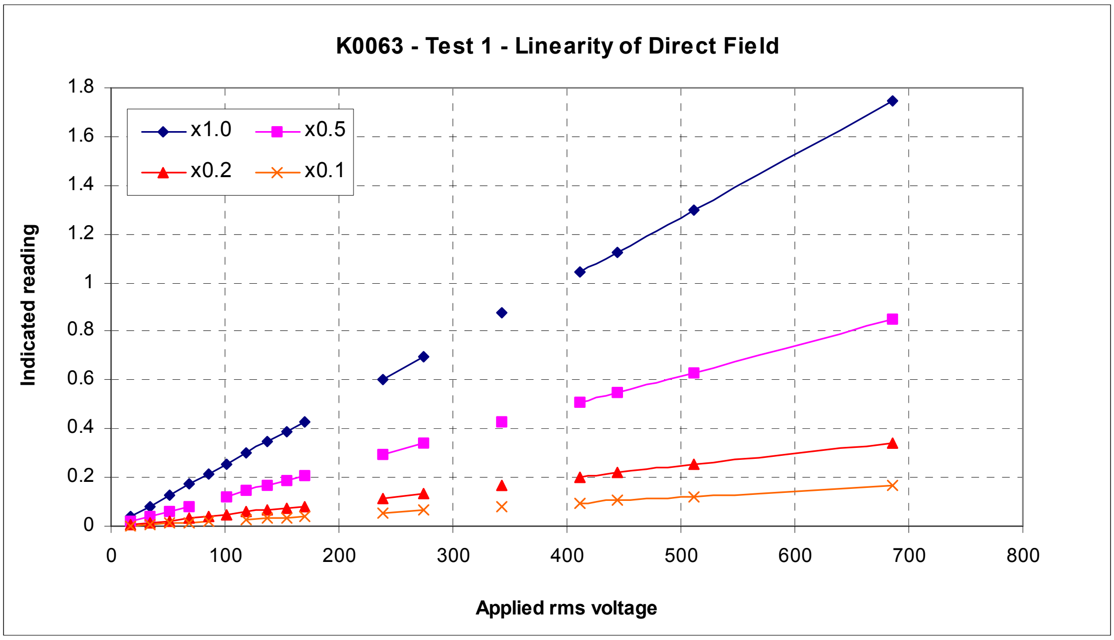
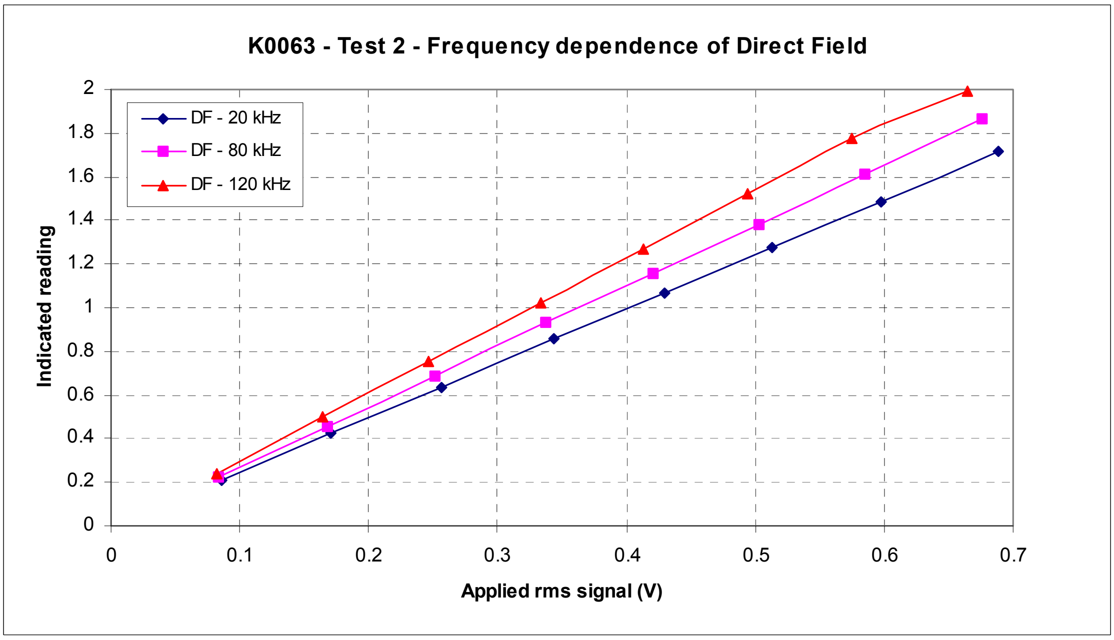


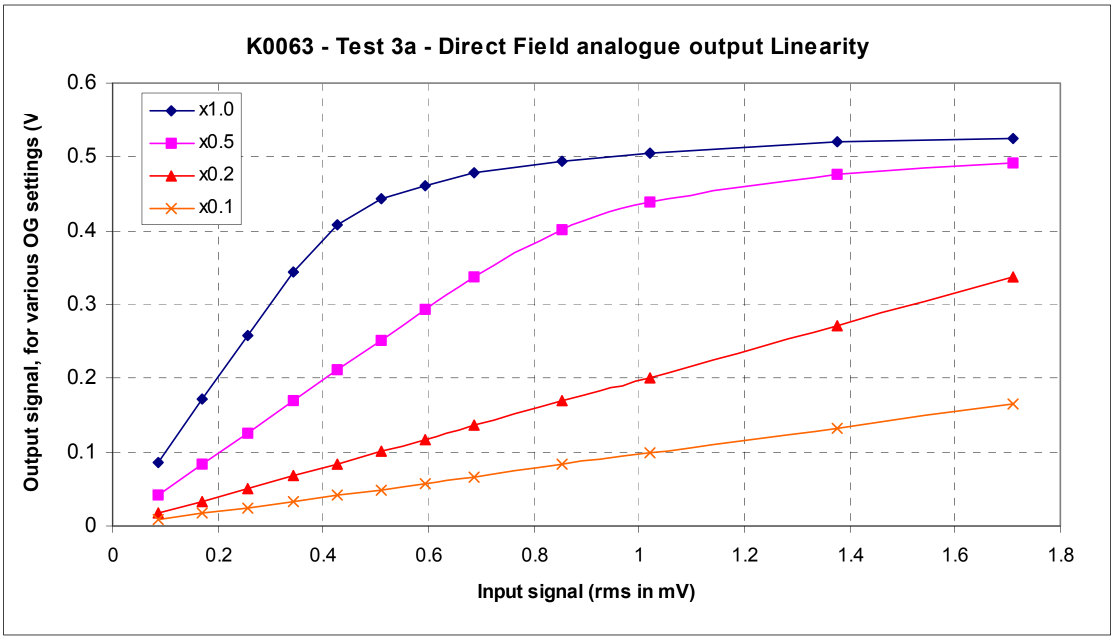
Figure B.1: Schematic diagram of electrical testing arrangement

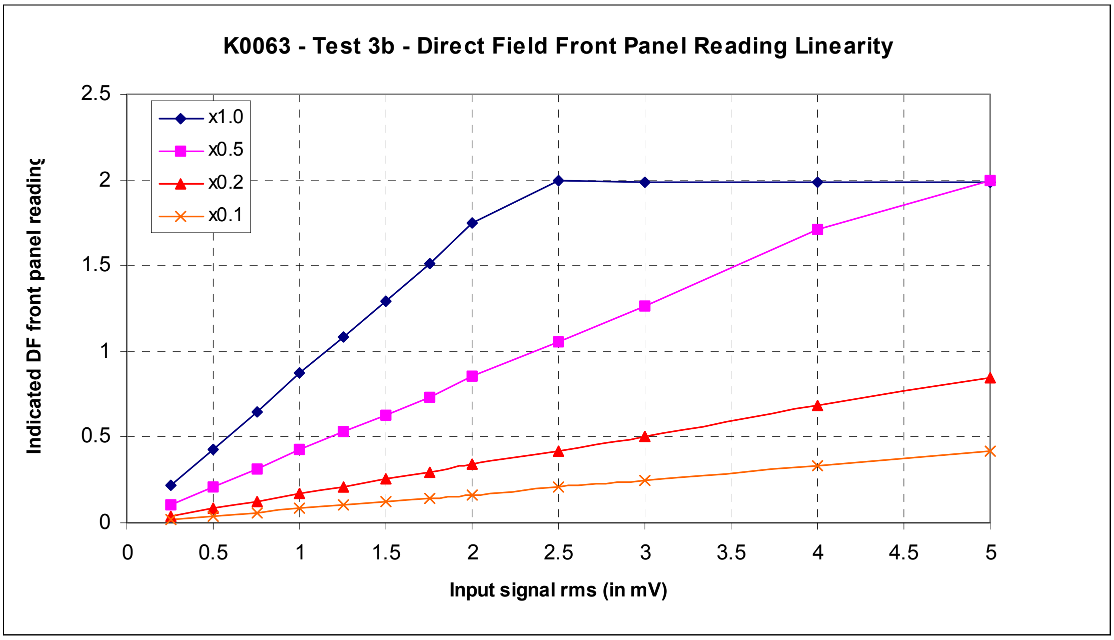
Depending on the type of tests carried out, either the Wavetek attenuator (HF channel testing) or the 300 kHz low pass filter (LF and SLF channel testing) was used in the signal chain. The Rohde and Schwarz URE3 RMS meter was used to monitor the input signal level to the Cavimeter, and also, where tested, the output level from the BNC analogue outputs on the LF and HF channels.

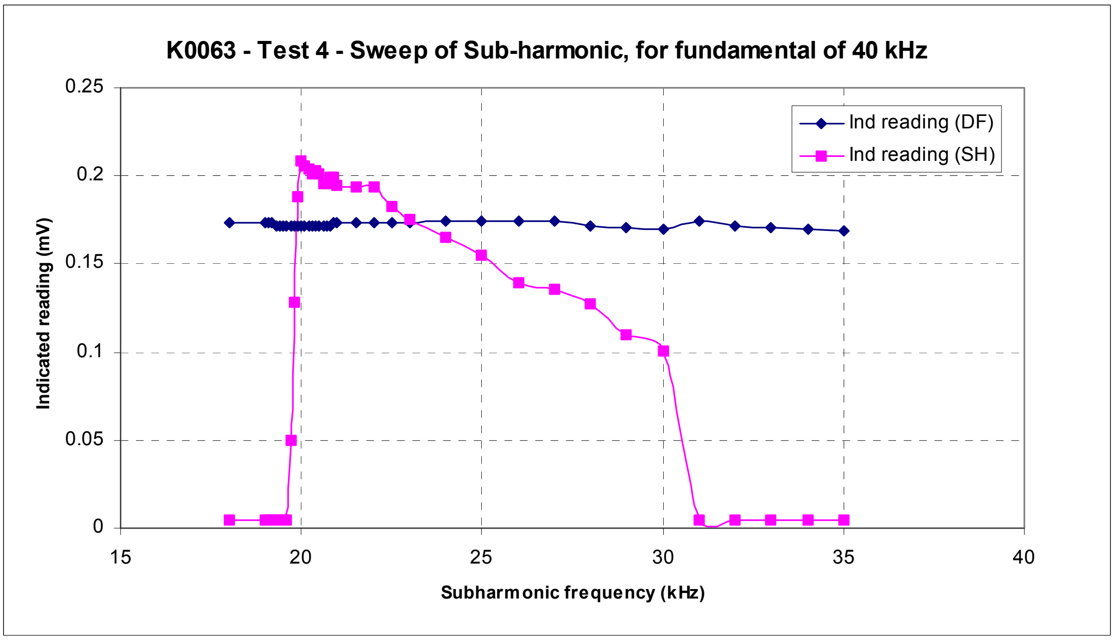
B.1 CAVIMETER K0063

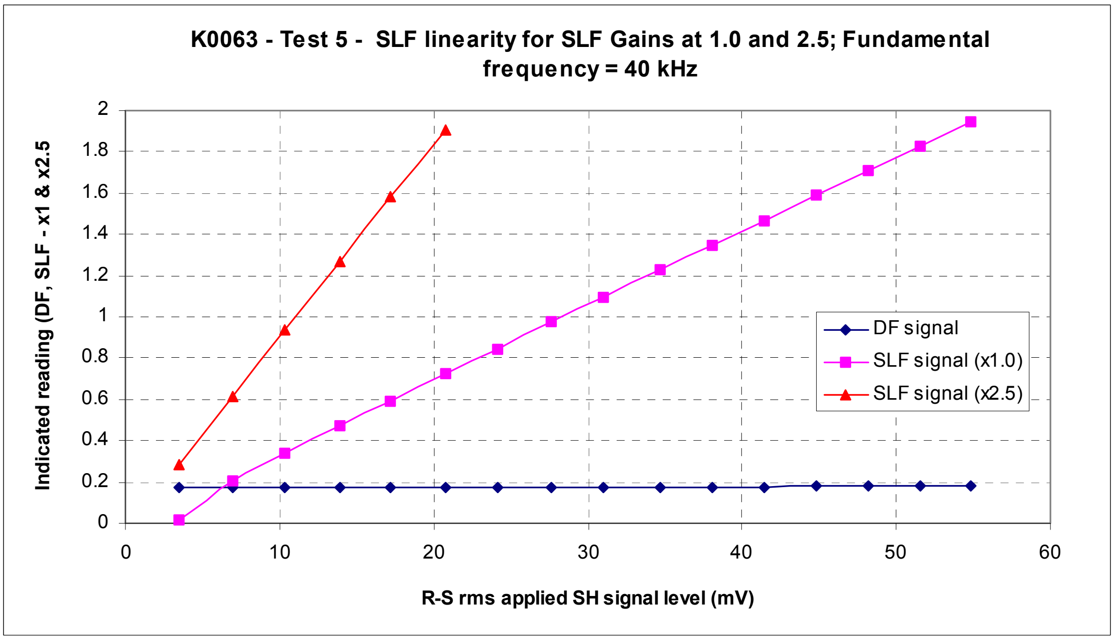


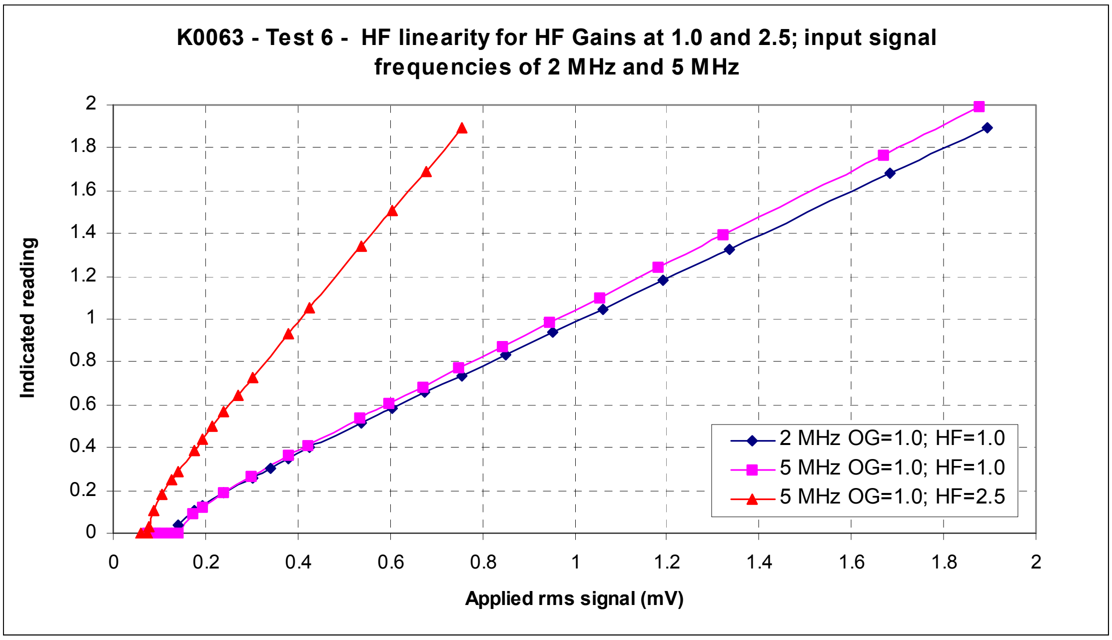


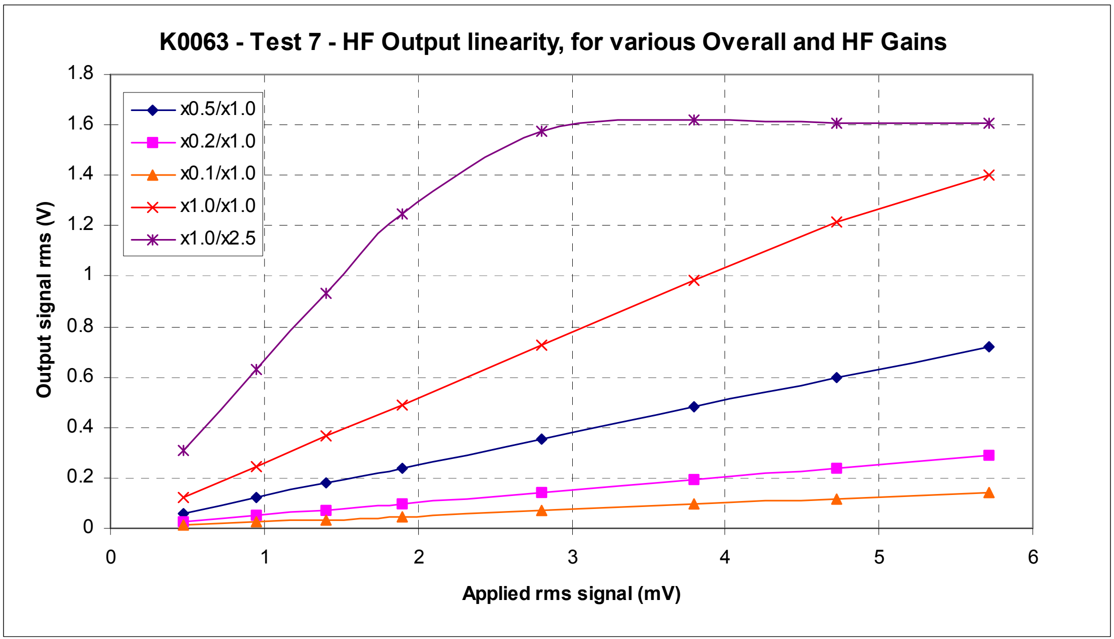

K0063 - Test 3a - Direct Field analogue output Linearity
Output signal, for various OG settings (V
Input signal (rms in mV)
x1.0
x0.5
x0.2
x0.1
0
0.1
0.2
0.3
0.4
0.5
0.6
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8


K0063 - Test 3b - Direct Field Front Panel Reading Linearity
Indicated DF front panel reading
Input signal rms (in mV)
x1.0
x0.5
x0.2
x0.1
0
0.5
1
1.5
2
2.5
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
5

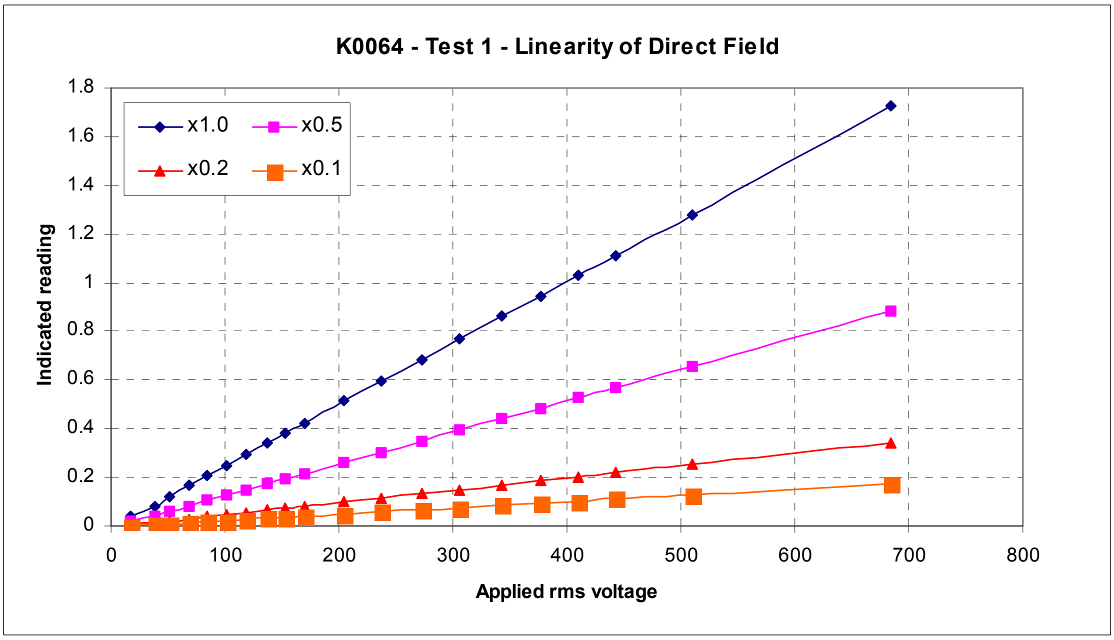

K0063 - Test 4 - Sweep of Sub-harmonic, for fundamental of 40 kHz
Indicated reading (mV)
0.25
0.2
0.15
0.1
0.05
0
15
20
25
30
35
40
Subharmonic frequency (kHz)
Ind reading (DF)
Ind reading (SH)

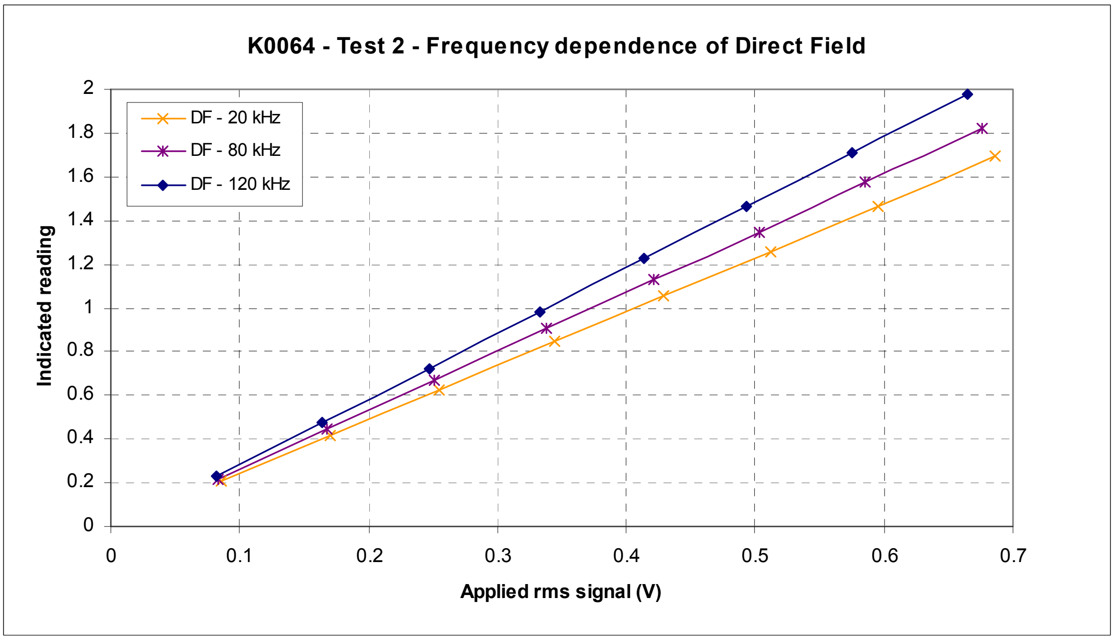

K0063 - Test 5 - SLF linearity for SLF Gains at 1.0 and 2.5; Fundamental frequency = 40 kHz
Indicated reading (DF, SLF - x1 & x2.5
2
1.8
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
10
20
30
40
50
60
R-S rms applied SH signal level (mV)
DF signal
SLF signal (x1.0)
SLF signal (x2.5)

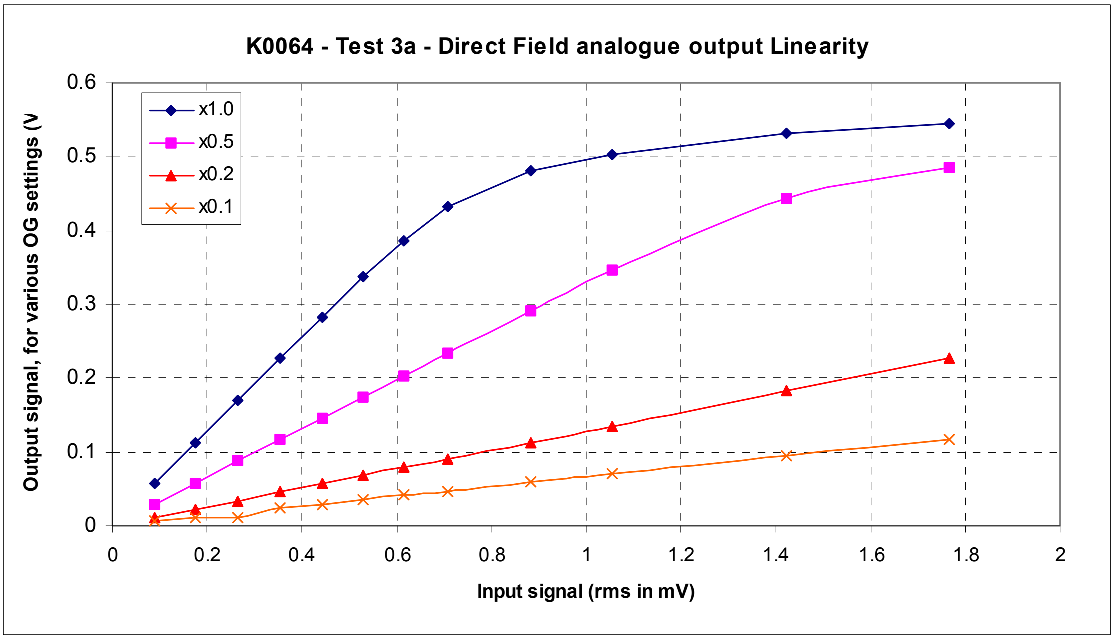

K0063 - Test 6 - HF linearity for HF Gains at 1.0 and 2.5; input signal frequencies of 2 MHz and 5 MHz
Indicated reading
Applied rms signal (mV)
2 MHz OG=1.0; HF=1.0
5 MHz OG=1.0; HF=1.0
5 MHz OG=1.0; HF=2.5

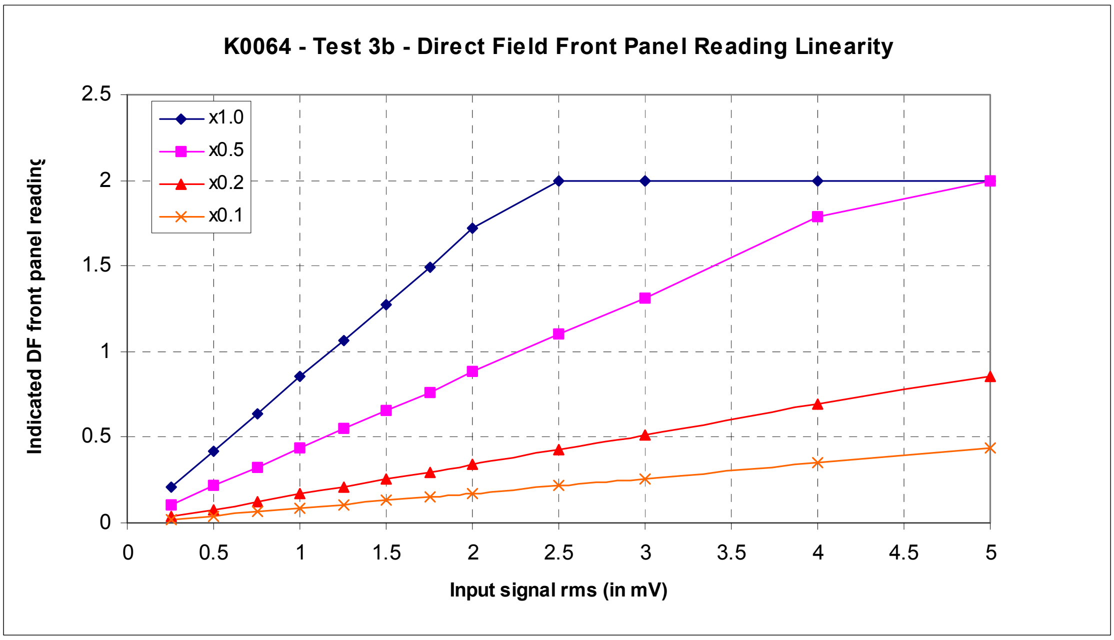

K0063 - Test 7 - HF Output linearity, for various Overall and HF Gains
Output signal rms (V)
Applied rms signal (mV)
x0.5/x1.0
x0.2/x1.0
x0.1/x1.0
x1.0/x1.0
x1.0/x2.5

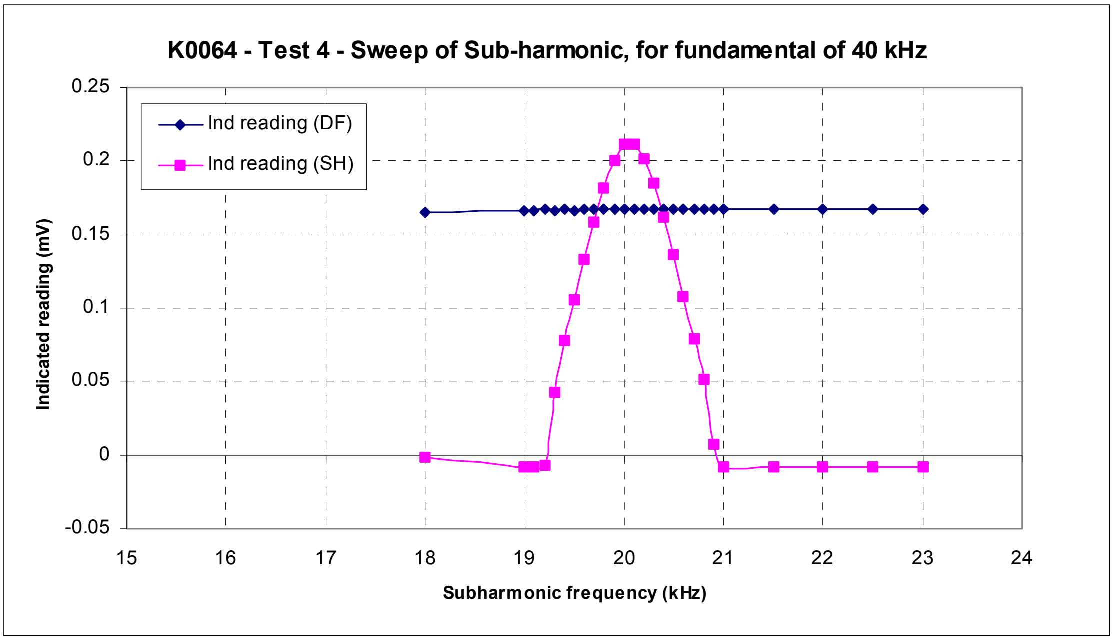
B.2 CAVIMETER K0064



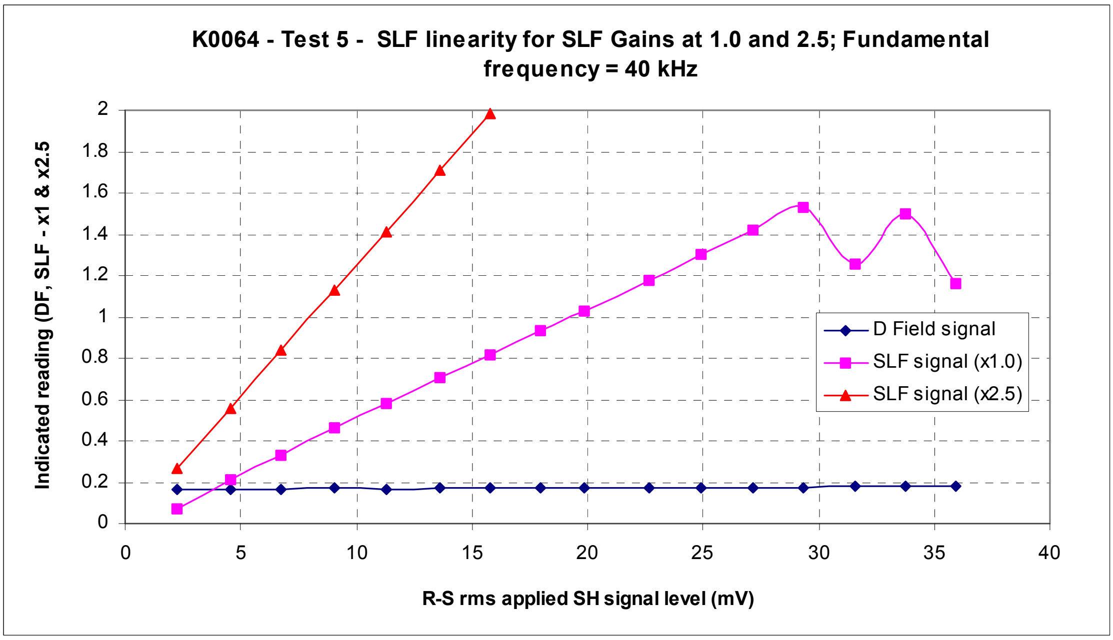



K0064 - Test 3a - Direct Field analogue output Linearity
Output signal, for various OG settings (V
Input signal (rms in mV)
x1.0
x0.5
x0.2
x0.1
0
0.1
0.2
0.3
0.4
0.5
0.6
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8
2

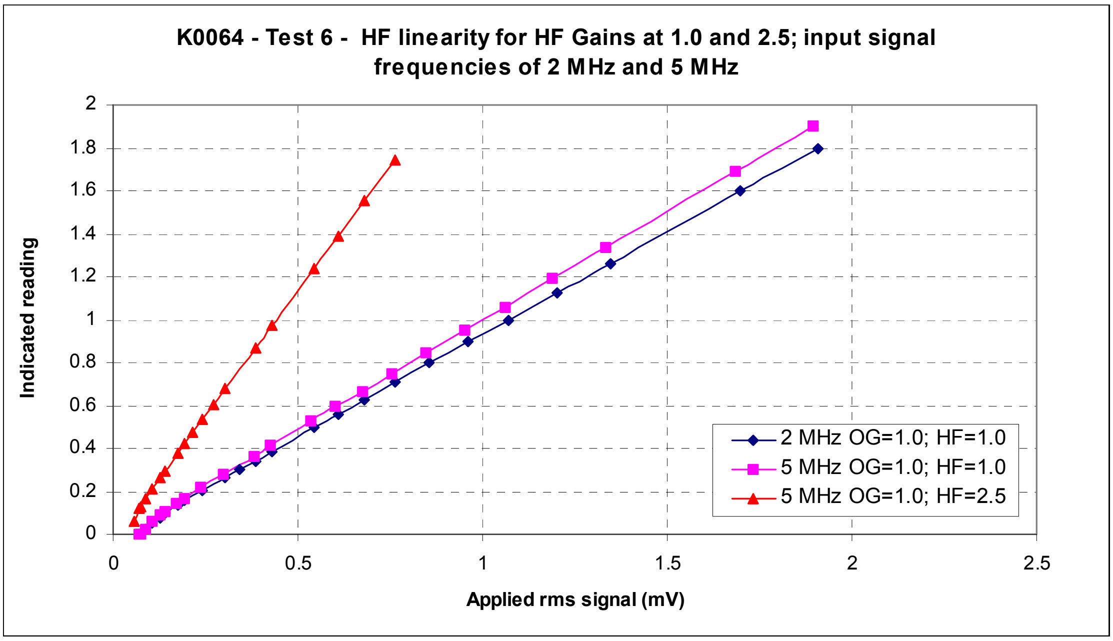

K0064 - Test 3b - Direct Field Front Panel Reading Linearity
Indicated DF front panel reading
Input signal rms (in mV)
x1.0
x0.5
x0.2
x0.1
0
0.5
1
1.5
2
2.5
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
5

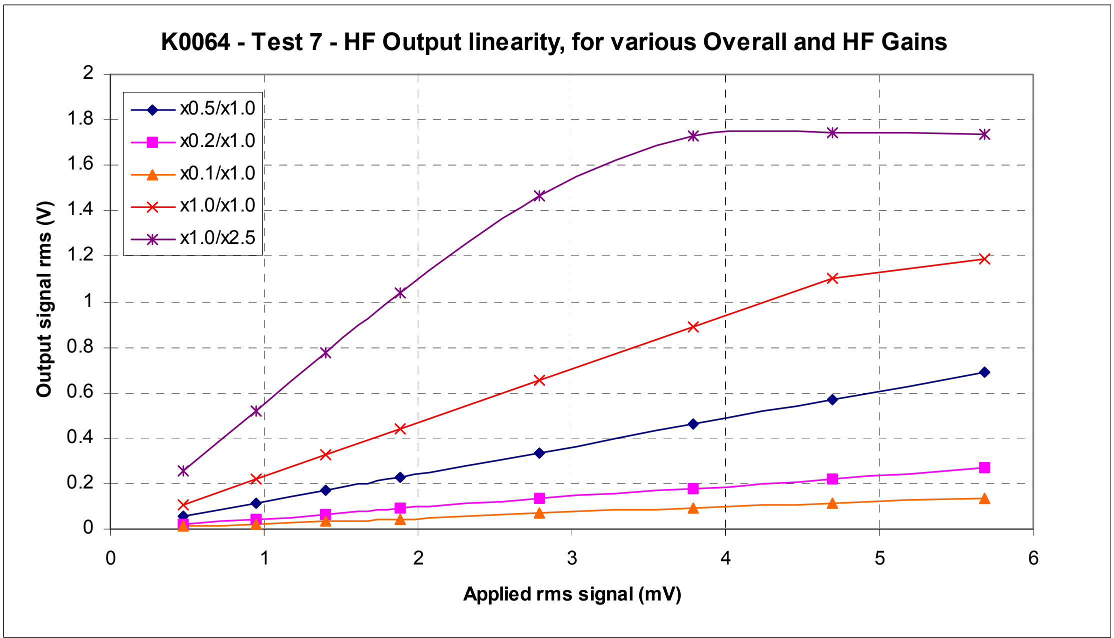


K0064 - Test 4 - Sweep of Sub-harmonic, for fundamental of 40 kHz
Ind reading (DF)
Ind reading (SH)
Indicated reading (mV)
0.25
0.2
0.15
0.1
0.05
0
-0.05
15
16
17
18
19
20
21
22
23
24
Subharmonic frequency (kHz)

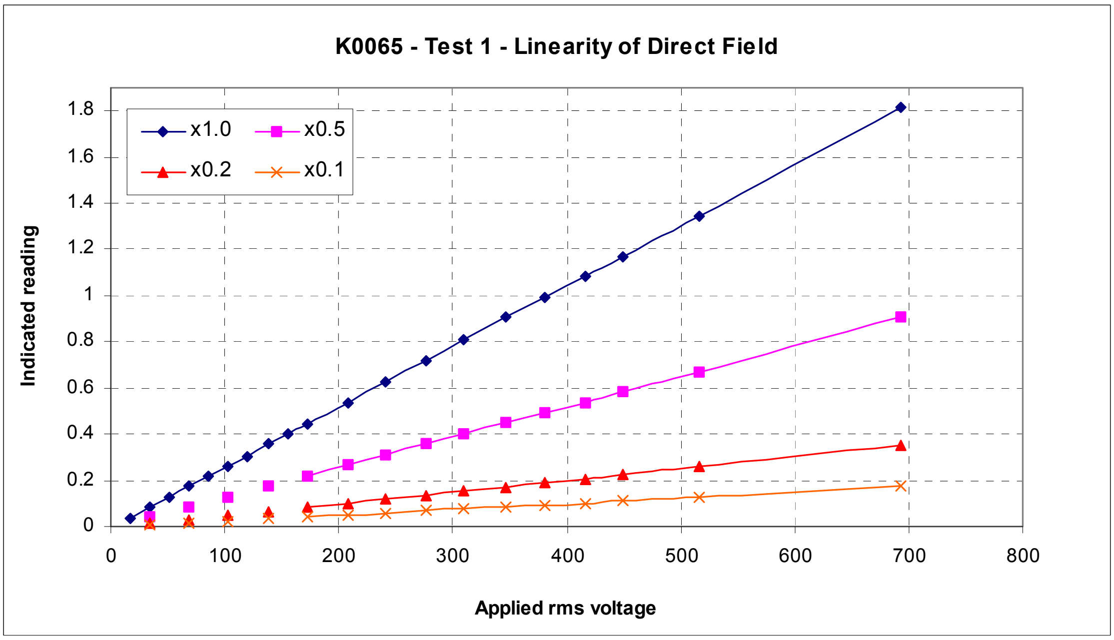


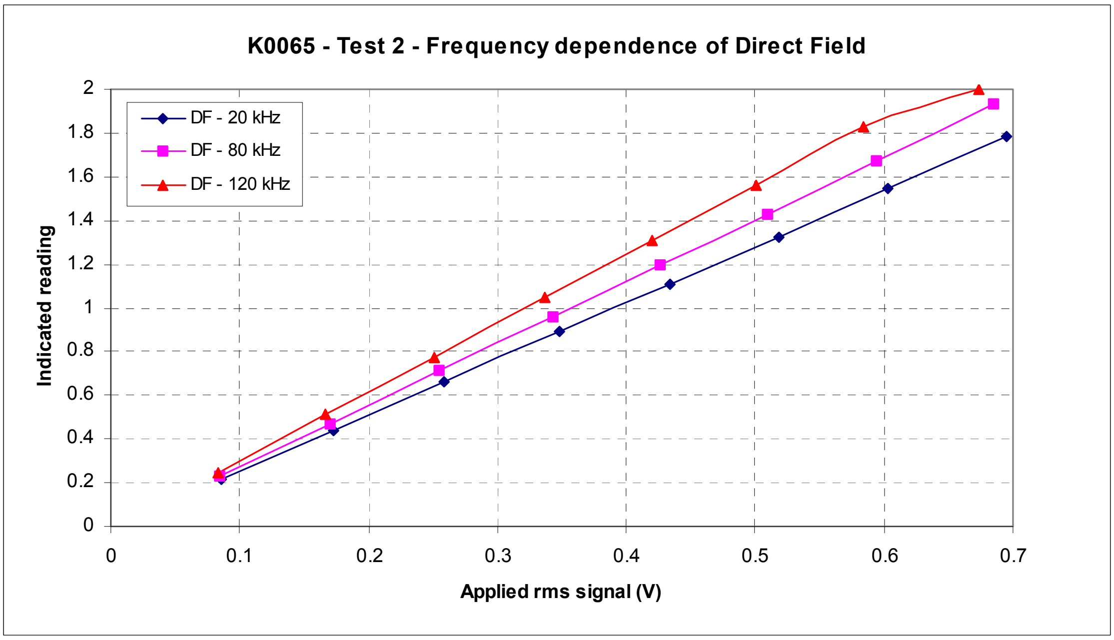
K0064 - Test 5 - SLF linearity for SLF Gains at 1.0 and 2.5; Fundamental frequency = 40 kHz
Indicated reading (DF, SLF - x1 & x2.5
D Field signal
SLF signal (x1.0)
SLF signal (x2.5)
2
1.8
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
0
5
10
15
20
25
30
35
40
R-S rms applied SH signal level (mV)

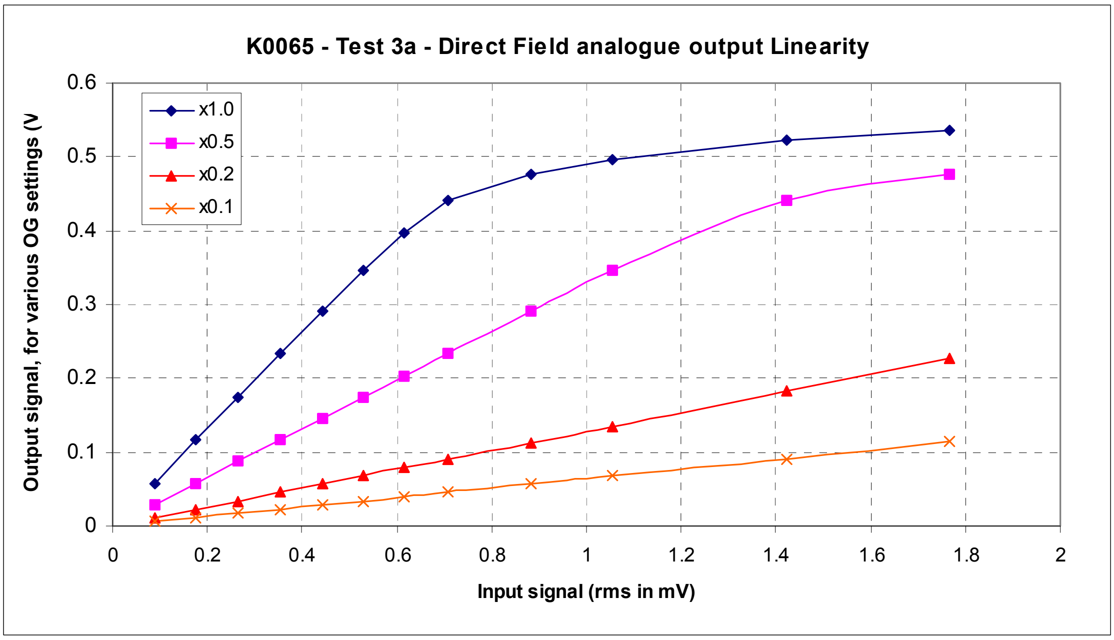

K0064 - Test 6 - HF linearity for HF Gains at 1.0 and 2.5; input signal frequencies of 2 MHz and 5 MHz
Indicated reading
Applied rms signal (mV)
2 MHz OG=1.0; HF=1.0
5 MHz OG=1.0; HF=1.0
5 MHz OG=1.0; HF=2.5
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8
2
0
0.5
1
1.5
2
2.5

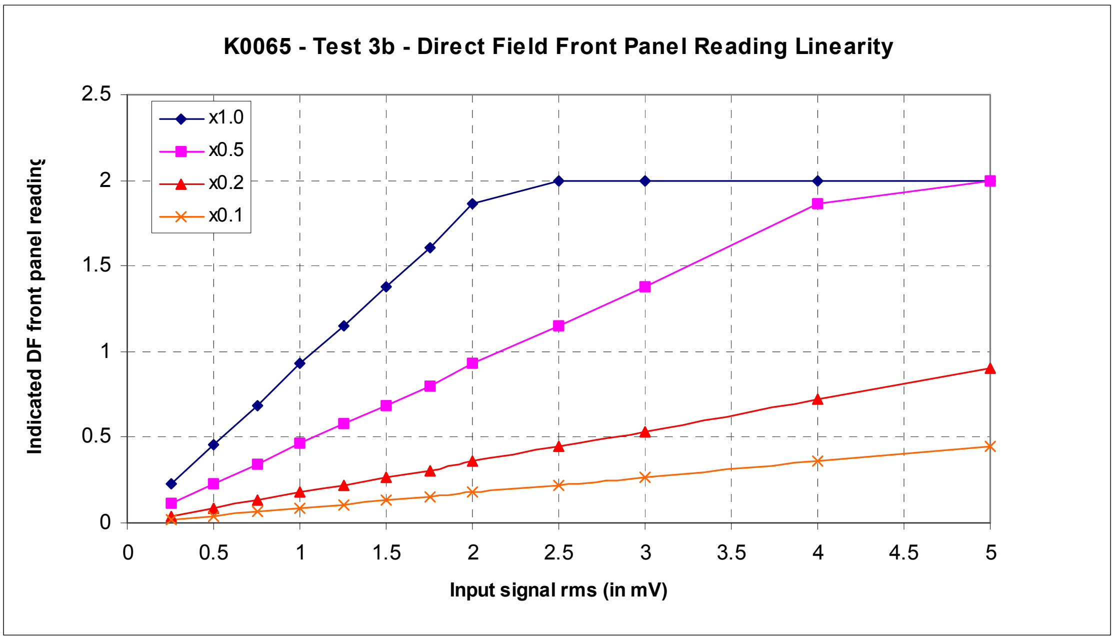

K0064 - Test 7 - HF Output linearity, for various Overall and HF Gains
Output signal rms (V)
Applied rms signal (mV)
x0.5/x1.0
x0.2/x1.0
x0.1/x1.0
x1.0/x1.0
x1.0/x2.5
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8
2
0
1
2
3
4
5
6

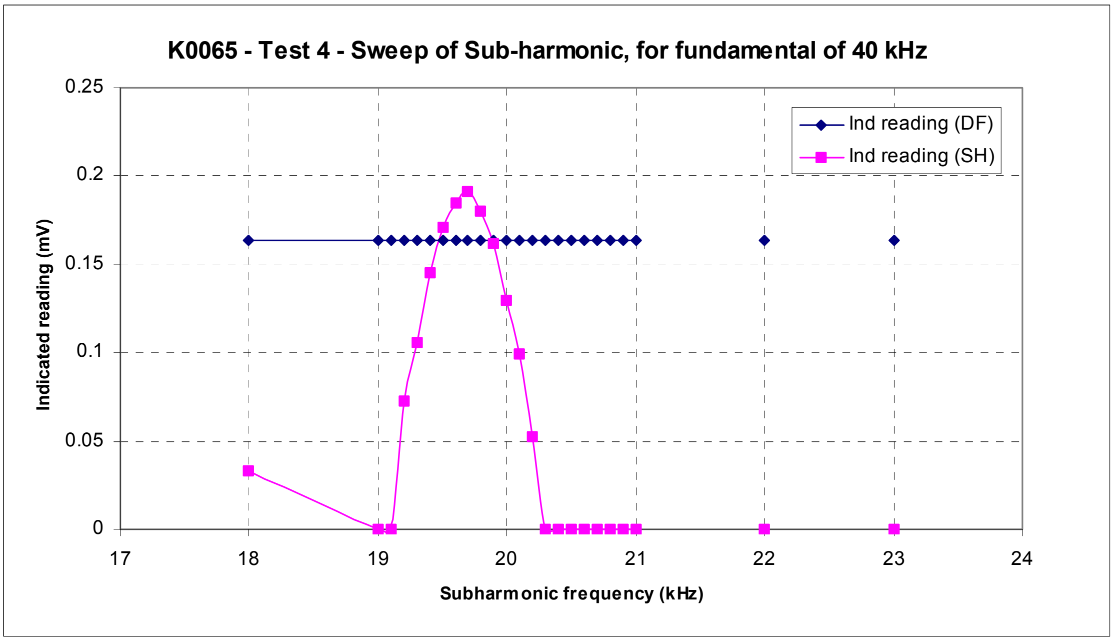
B.3 CAVIMETER K0065

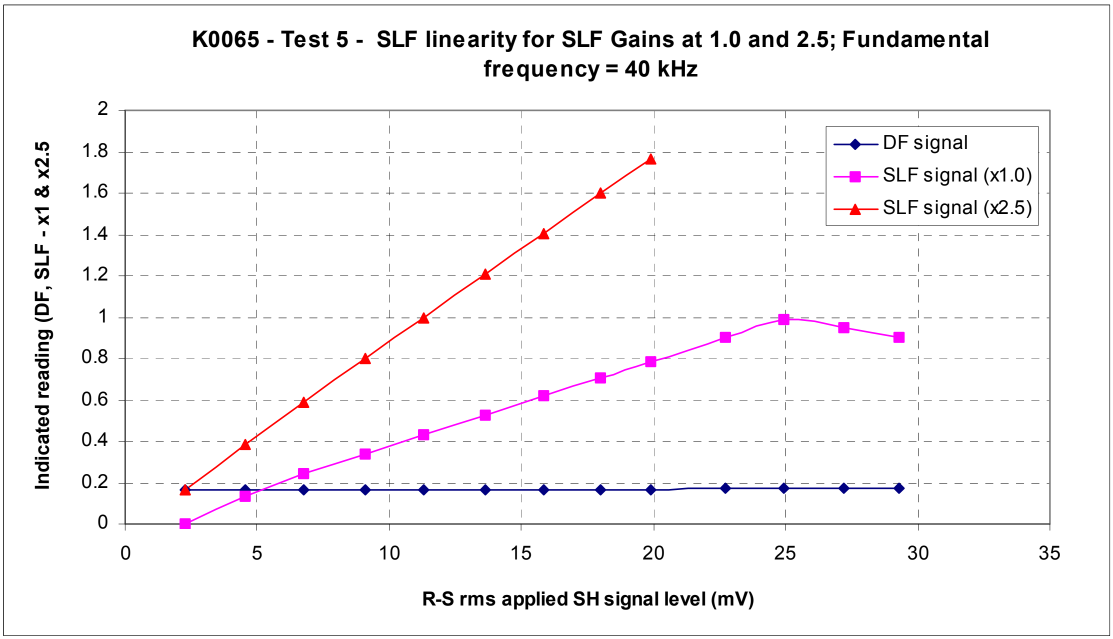


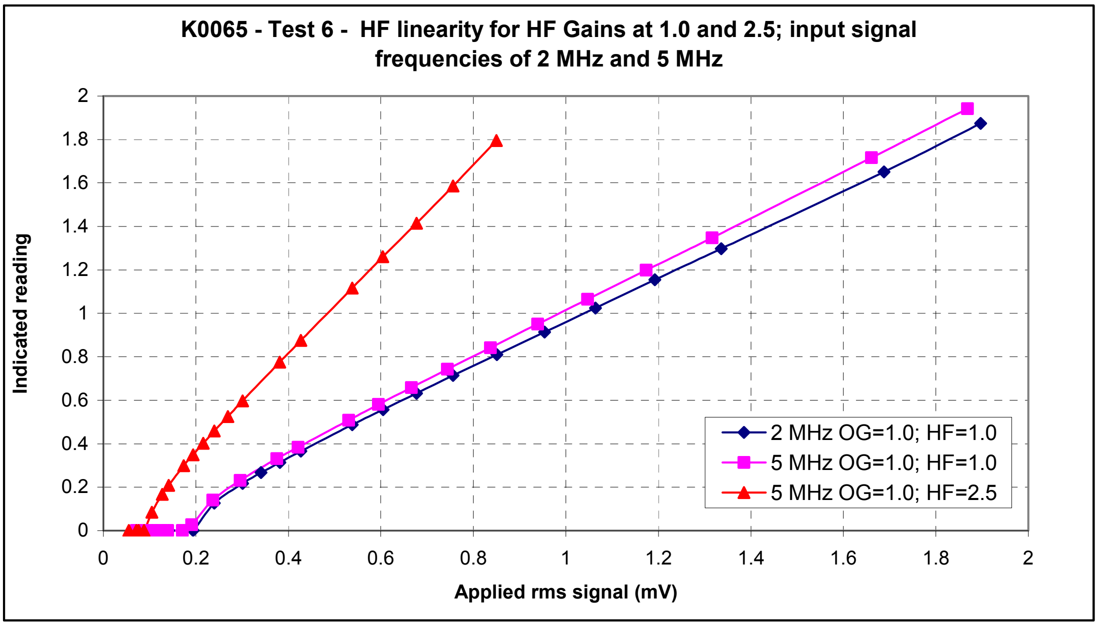


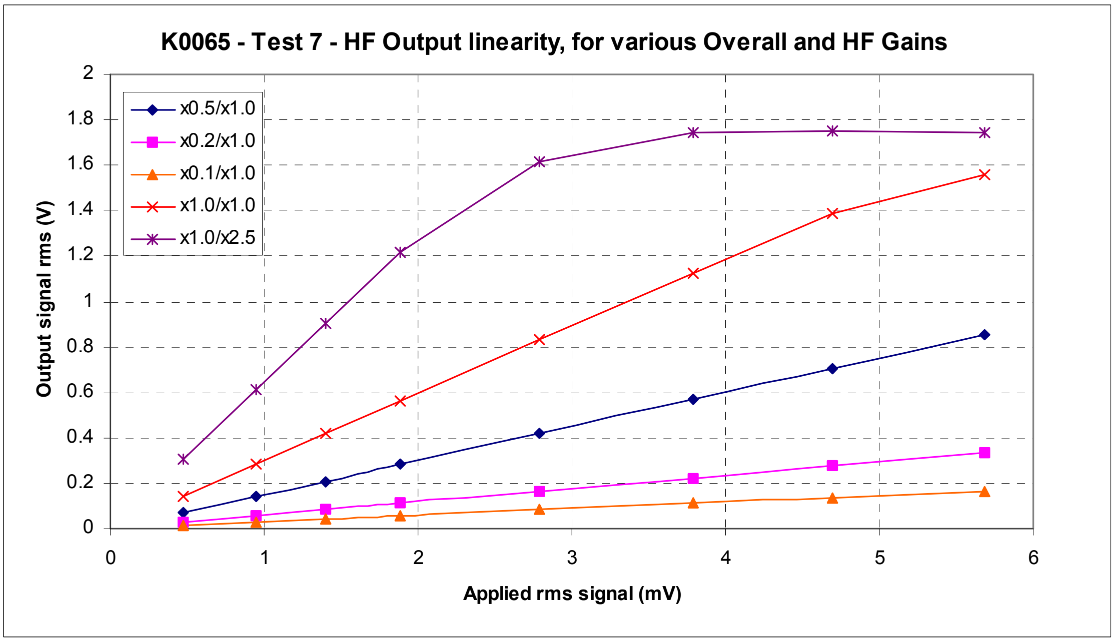

K0065 - Test 3a - Direct Field analogue output Linearity
Output signal, for various OG settings (V
Input signal (rms in mV)
x1.0
x0.5
x0.2
x0.1
0
0.1
0.2
0.3
0.4
0.5
0.6
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8
2


K0065 - Test 3b - Direct Field Front Panel Reading Linearity
Indicated DF front panel reading
Input signal rms (in mV)
x1.0
x0.5
x0.2
x0.1
0
0.5
1
1.5
2
2.5
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
5

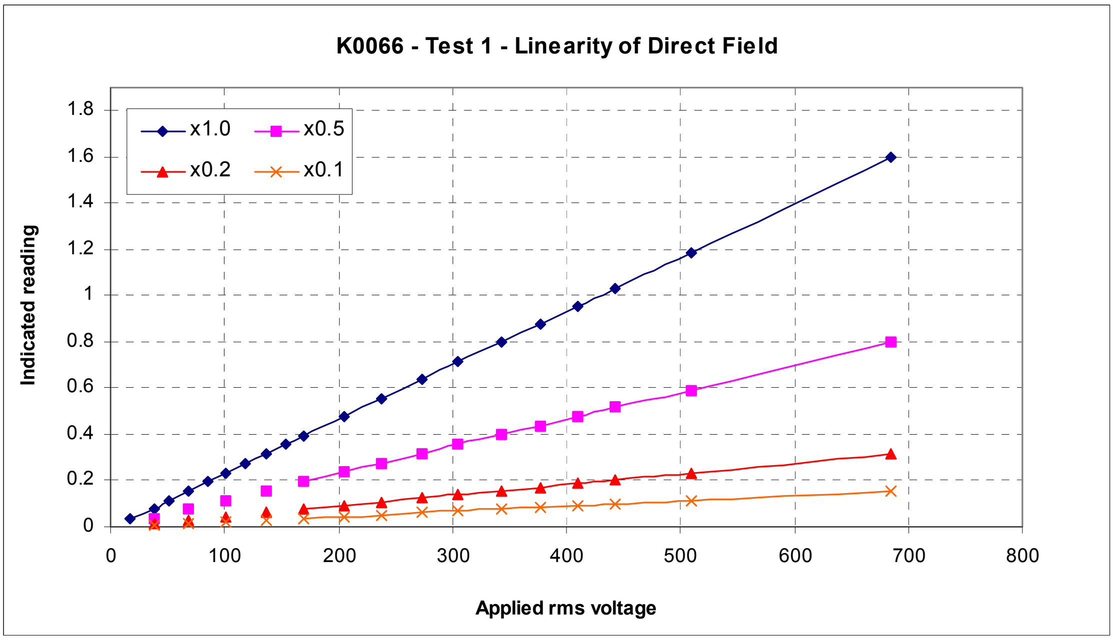

K0065 - Test 4 - Sweep of Sub-harmonic, for fundamental of 40 kHz
Indicated reading (mV)
Subharmonic frequency (kHz)
Ind reading (DF)
Ind reading (SH)
0.25
0.2
0.15
0.1
0.05
0
17
18
19
20
21
22
23
24

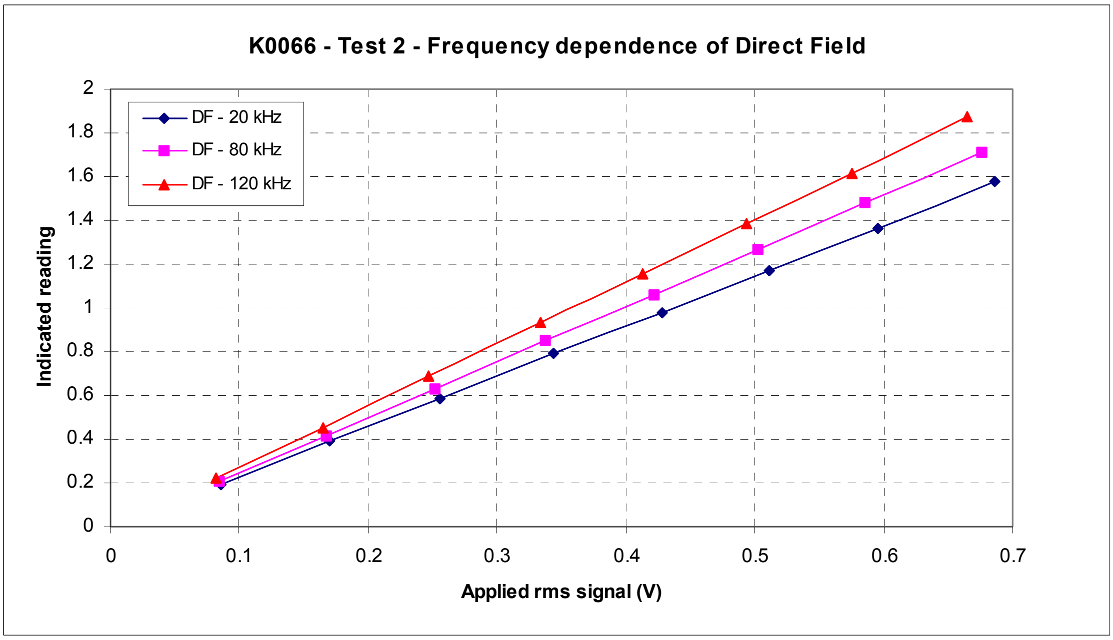

K0065 - Test 5 - SLF linearity for SLF Gains at 1.0 and 2.5; Fundamental frequency = 40 kHz
Indicated reading (DF, SLF - x1 & x2.5
R-S rms applied SH signal level (mV)
DF signal
SLF signal (x1.0)
SLF signal (x2.5)
2
1.8
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
0
5
10
15
20
25
30
35

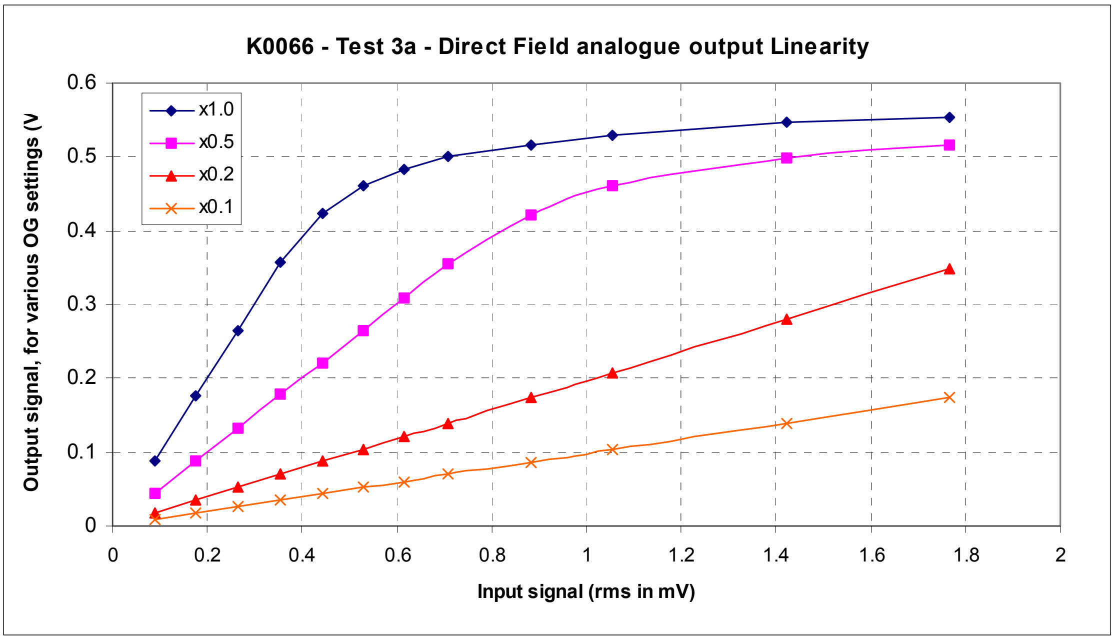

K0065 - Test 6 - HF linearity for HF Gains at 1.0 and 2.5; input signal frequencies of 2 MHz and 5 MHz
Indicated reading
Applied rms signal (mV)
2 MHz OG=1.0; HF=1.0
5 MHz OG=1.0; HF=1.0
5 MHz OG=1.0; HF=2.5

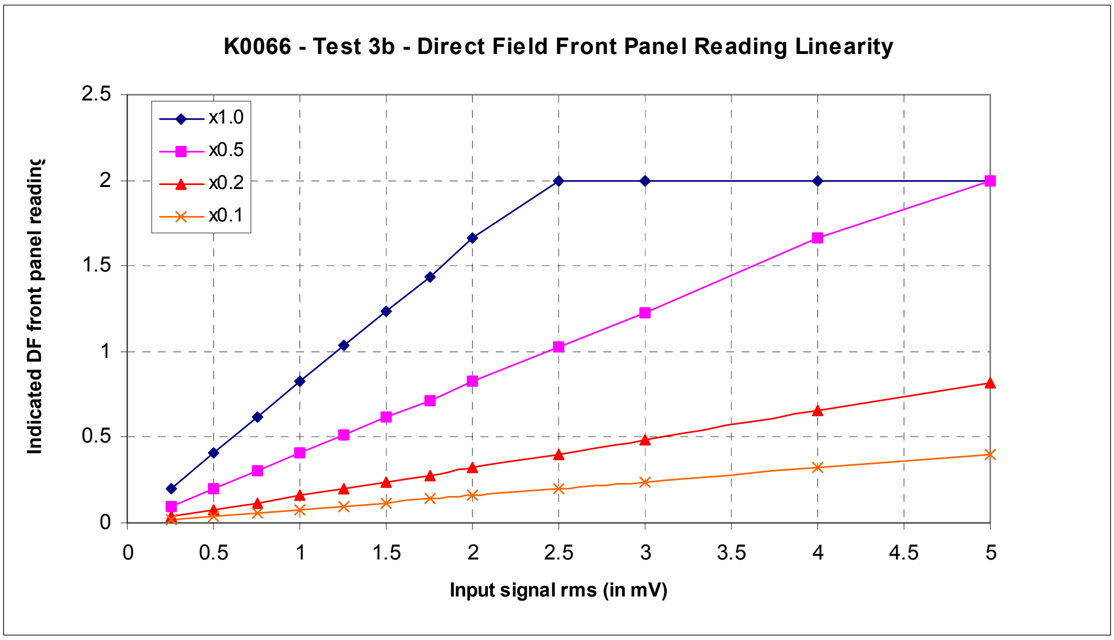

K0065 - Test 7 - HF Output linearity, for various Overall and HF Gains
Output signal rms (V)
Applied rms signal (mV)
x0.5/x1.0
x0.2/x1.0
x0.1/x1.0
x1.0/x1.0
x1.0/x2.5

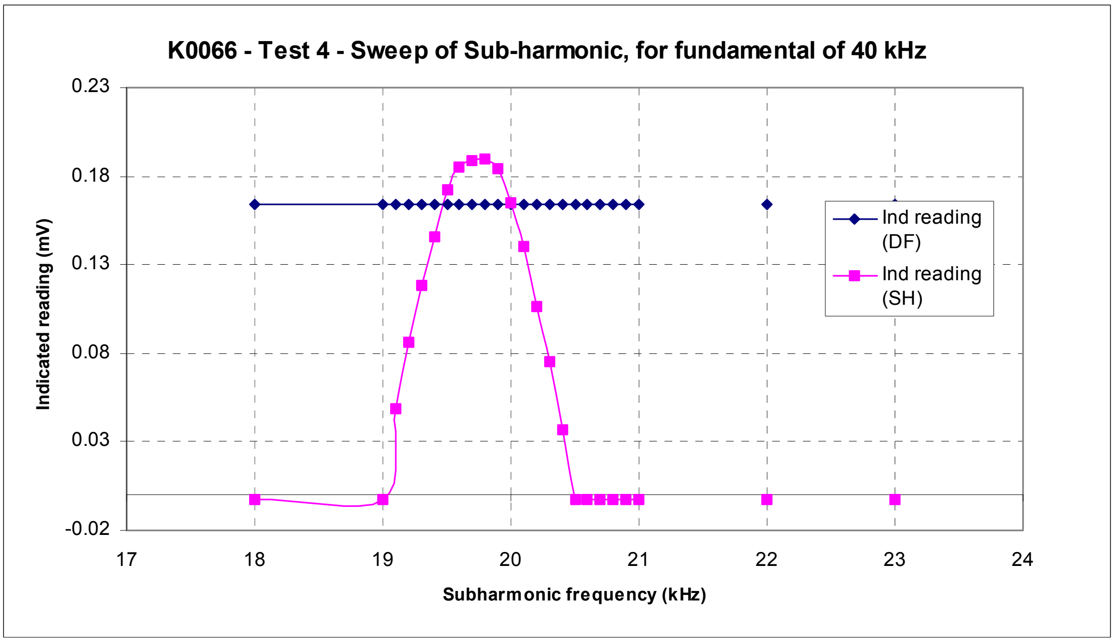
B.4 CAVIMETER K0066

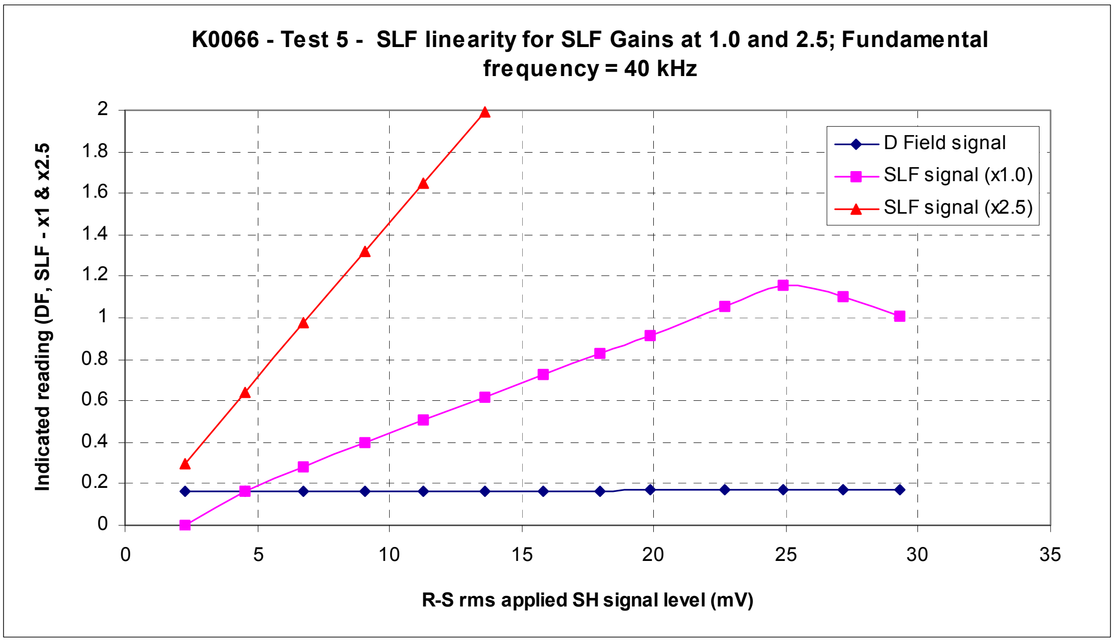


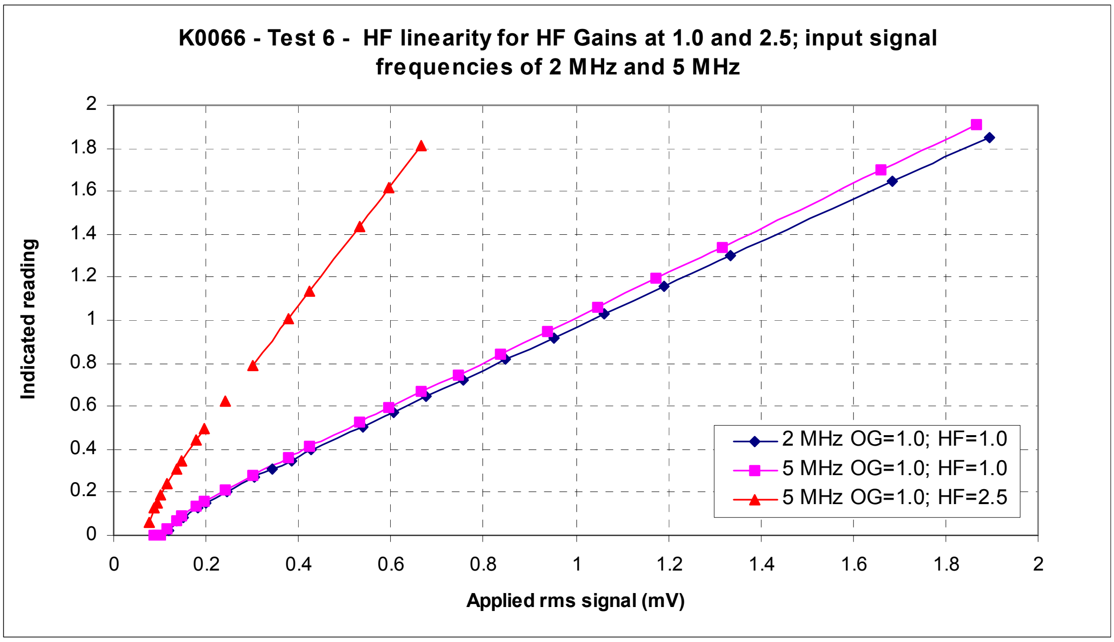


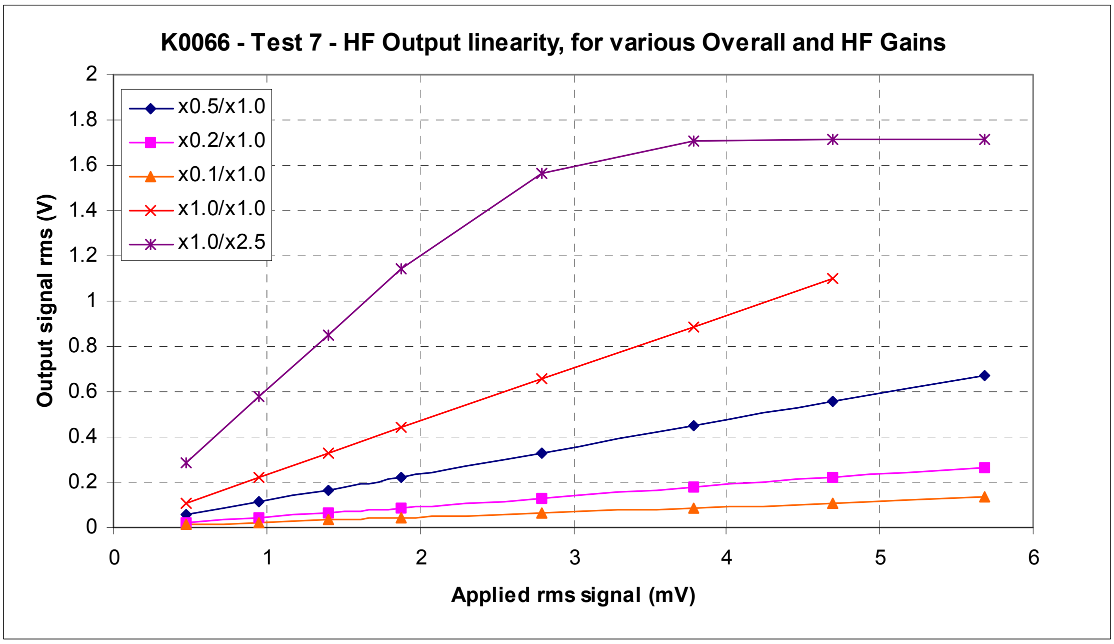

K0066 - Test 3a - Direct Field analogue output Linearity
Output signal, for various OG settings (V
Input signal (rms in mV)
x1.0
x0.5
x0.2
x0.1
0
0.1
0.2
0.3
0.4
0.5
0.6
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8
2


K0066 - Test 3b - Direct Field Front Panel Reading Linearity
Indicated DF front panel reading
Input signal rms (in mV)
x1.0
x0.5
x0.2
x0.1
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
5

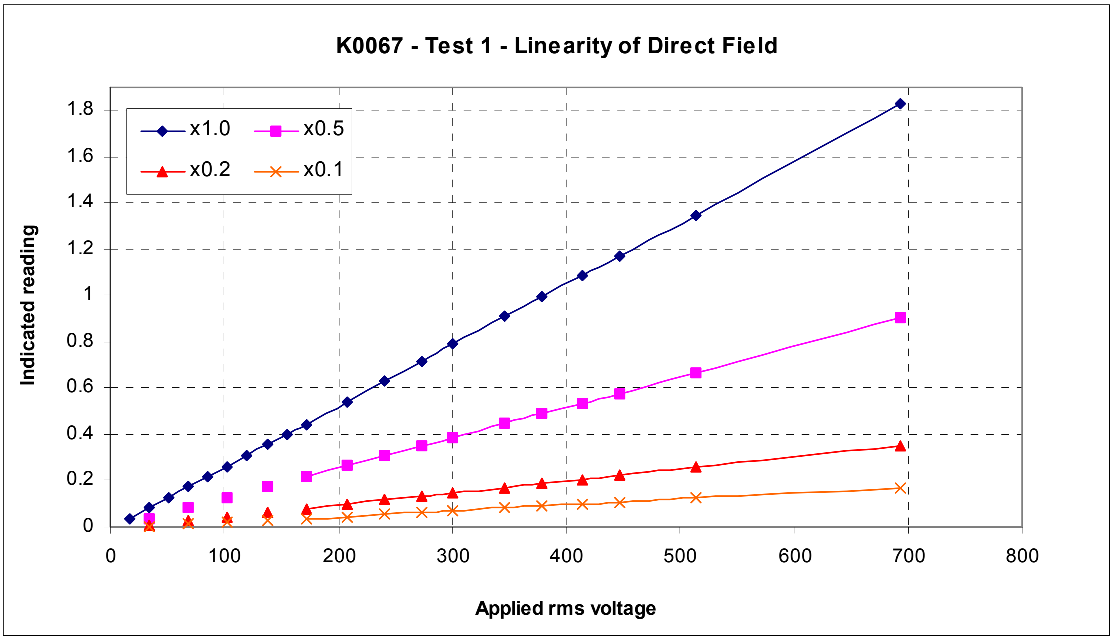

K0066 - Test 4 - Sweep of Sub-harmonic, for fundamental of 40 kHz
Indicated reading (mV)
0.23
0.18
0.13
0.08
0.03
-0.02
17
18
19
20
21
22
23
24
Subharmonic frequency (kHz)
Ind reading (DF)
Ind reading (SH)

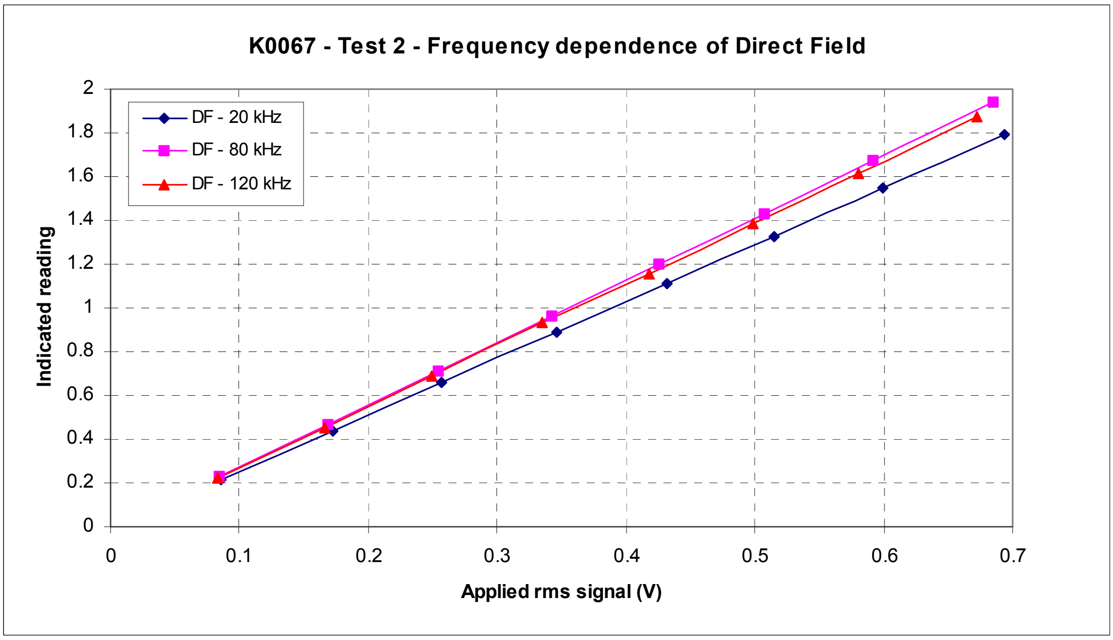

K0066 - Test 5 - SLF linearity for SLF Gains at 1.0 and 2.5; Fundamental frequency = 40 kHz
Indicated reading (DF, SLF - x1 & x2.5
2
1.8
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
0
5
10
15
20
25
30
35
R-S rms applied SH signal level (mV)
D Field signal
SLF signal (x1.0)
SLF signal (x2.5)

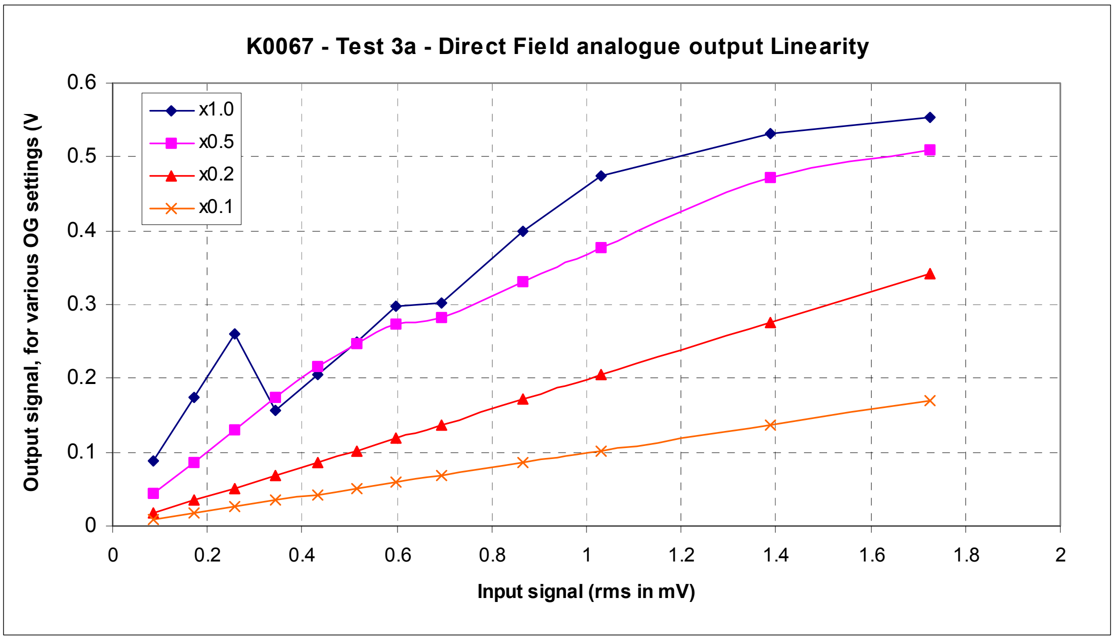

K0066 - Test 6 - HF linearity for HF Gains at 1.0 and 2.5; input signal frequencies of 2 MHz and 5 MHz
Indicated reading
Applied rms signal (mV)
2 MHz OG=1.0; HF=1.0
5 MHz OG=1.0; HF=1.0
5 MHz OG=1.0; HF=2.5

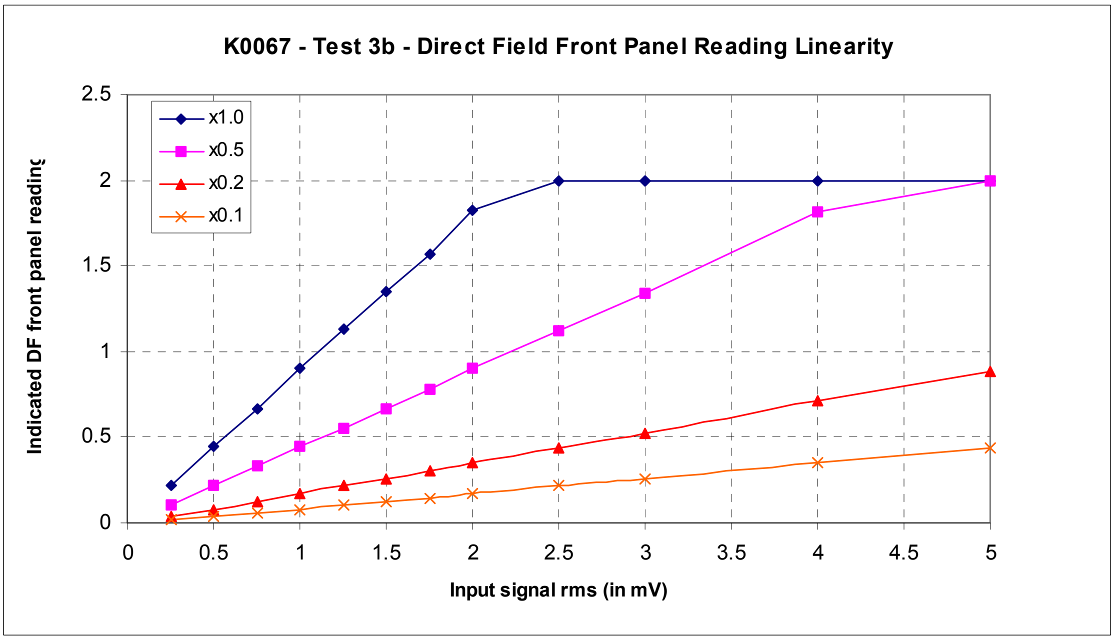

K0066 - Test 7 - HF Output linearity, for various Overall and HF Gains
Output signal rms (V)
Applied rms signal (mV)
x0.5/x1.0
x0.2/x1.0
x0.1/x1.0
x1.0/x1.0
x1.0/x2.5

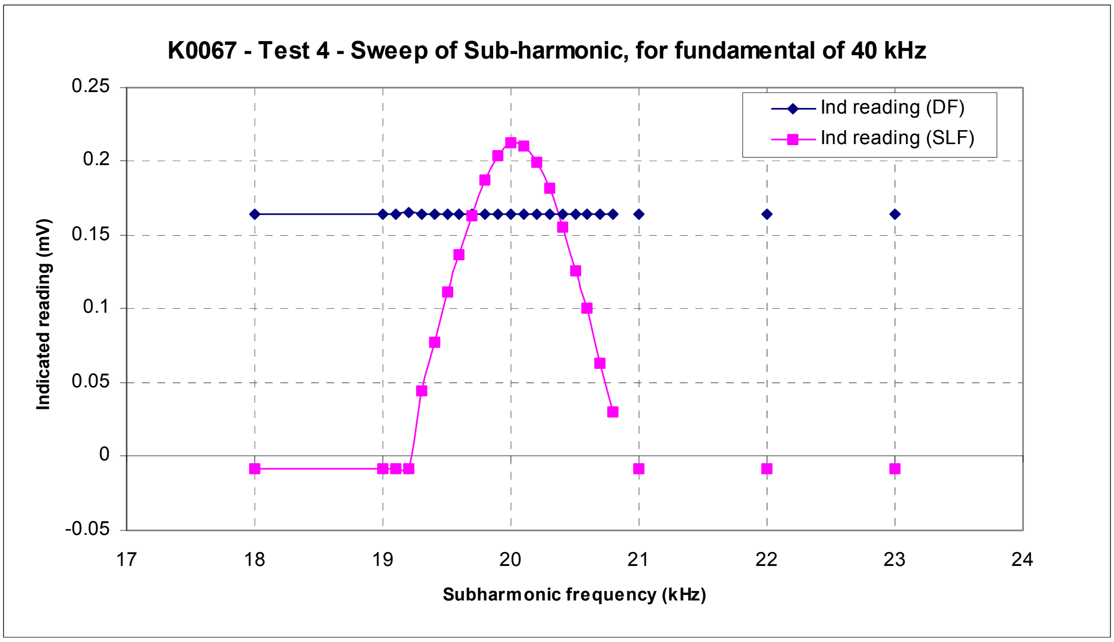
B.5 CAVIMETER K0067

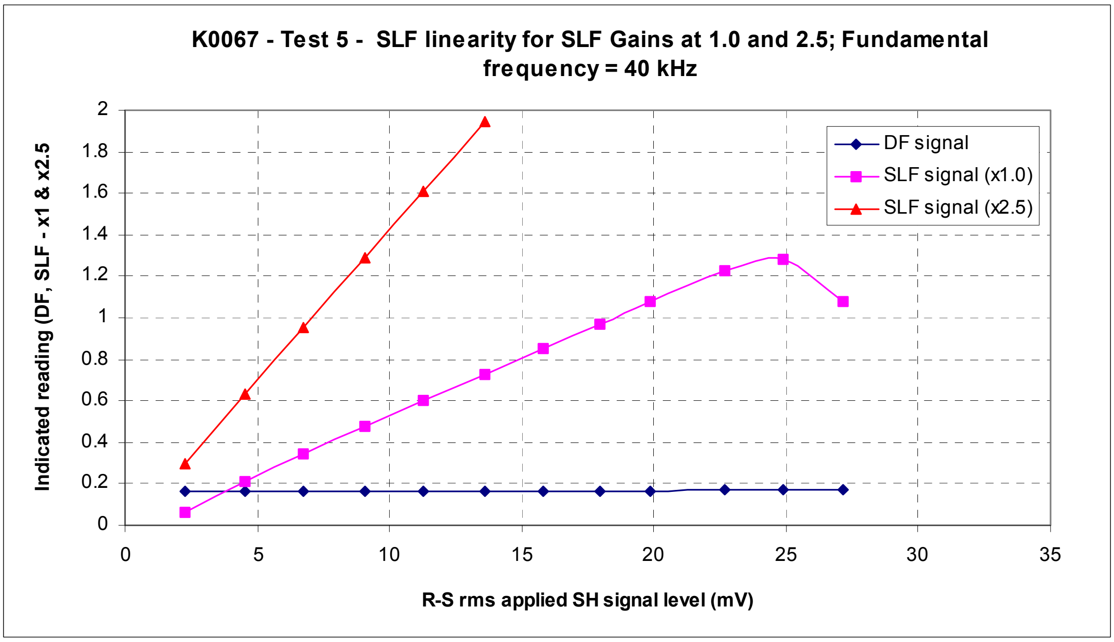


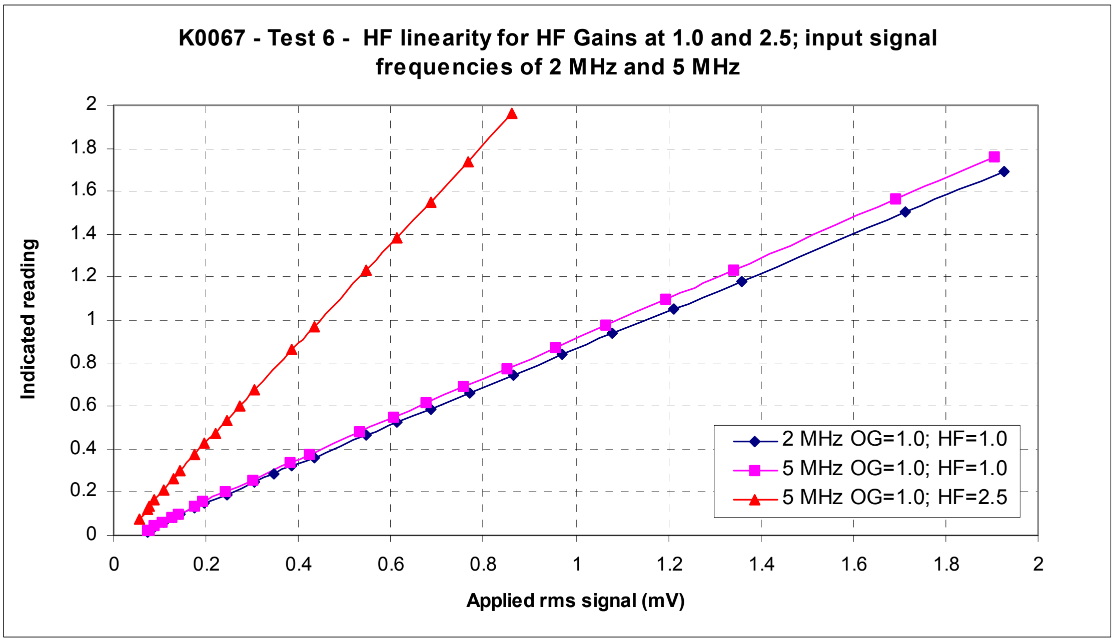


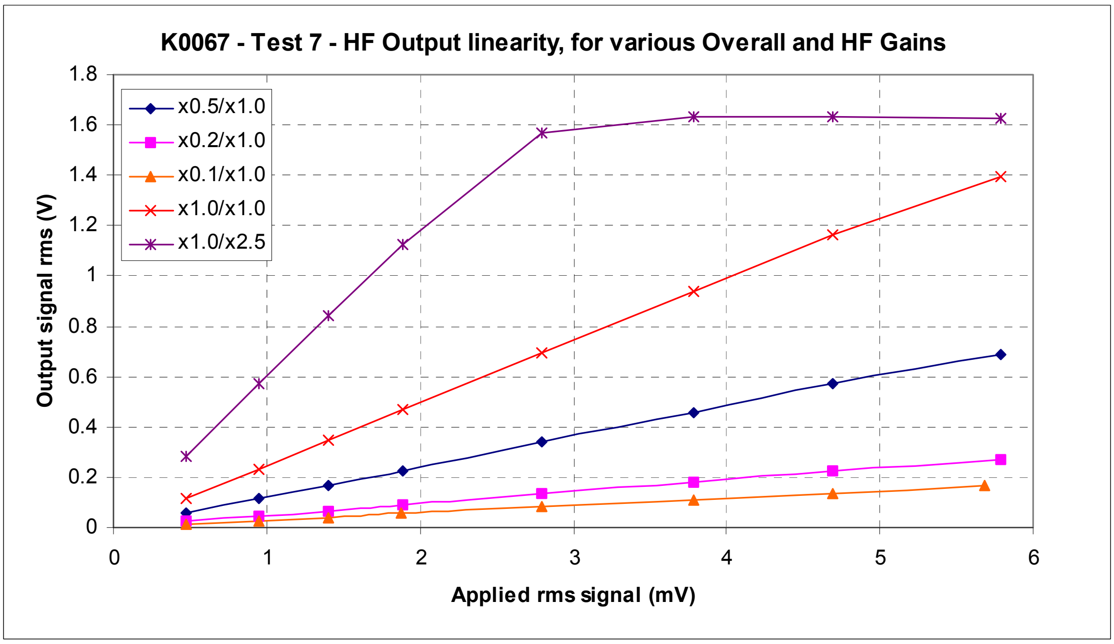

K0067 - Test 3a - Direct Field analogue output Linearity
x1.0
x0.5
x0.2
x0.1
Output signal, for various OG settings (V
Input signal (rms in mV)
0
0.1
0.2
0.3
0.4
0.5
0.6
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8
2


K0067 - Test 3b - Direct Field Front Panel Reading Linearity
x1.0
x0.5
x0.2
x0.1
Indicated DF front panel reading
Input signal rms (in mV)
0
0.5
1
1.5
2
2.5
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
5


K0067 - Test 4 - Sweep of Sub-harmonic, for fundamental of 40 kHz
Ind reading (DF)
Ind reading (SLF)
Indicated reading (mV)
0.25
0.2
0.15
0.1
0.05
0
-0.05
17
18
19
20
21
22
23
24
Subharmonic frequency (kHz)


K0067 - Test 5 - SLF linearity for SLF Gains at 1.0 and 2.5; Fundamental frequency = 40 kHz
DF signal
SLF signal (x1.0)
SLF signal (x2.5)
Indicated reading (DF, SLF - x1 & x2.5
2
1.8
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
0
5
10
15
20
25
30
35
R-S rms applied SH signal level (mV)


K0067 - Test 6 - HF linearity for HF Gains at 1.0 and 2.5; input signal frequencies of 2 MHz and 5 MHz
Indicated reading
Applied rms signal (mV)
2 MHz OG=1.0; HF=1.0
5 MHz OG=1.0; HF=1.0
5 MHz OG=1.0; HF=2.5
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8
2


K0067 - Test 7 - HF Output linearity, for various Overall and HF Gains
Output signal rms (V)
Applied rms signal (mV)
x0.5/x1.0
x0.2/x1.0
x0.1/x1.0
x1.0/x1.0
x1.0/x2.5
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8
0
1
2
3
4
5
6

APPENDIX C ACOUSTICAL TESTING OF CAVIMETERS

This Section contains details of the tests carried out on the Cavimeters using the 25 kHz reference vessel as described in Section 6.

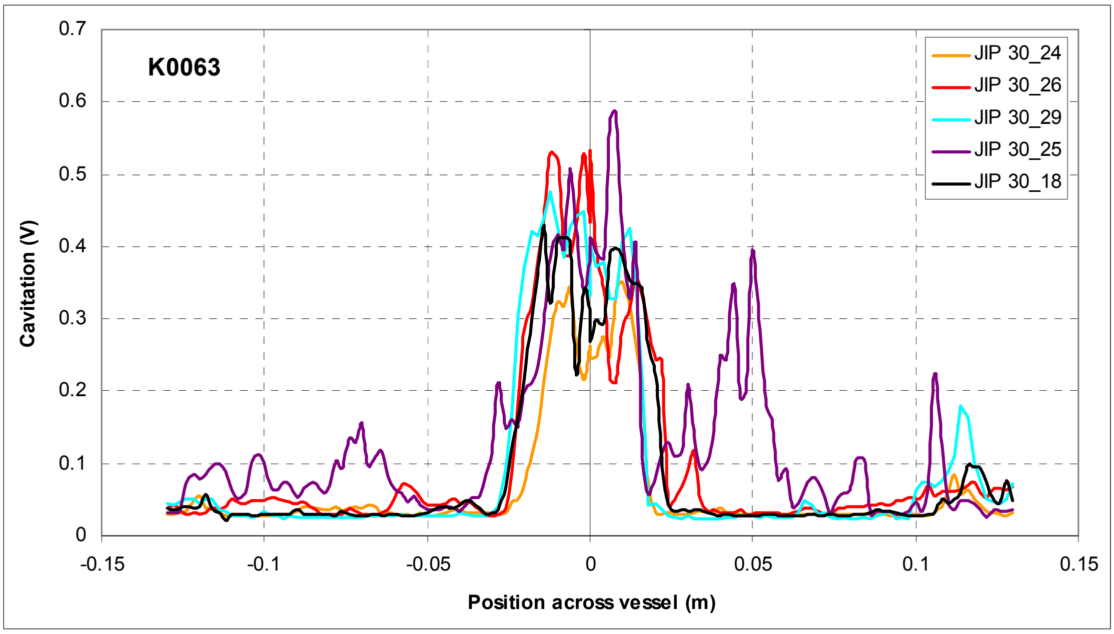


Figure C.1: 100 W scans carried out for Cavimeter K0063 and five sensors

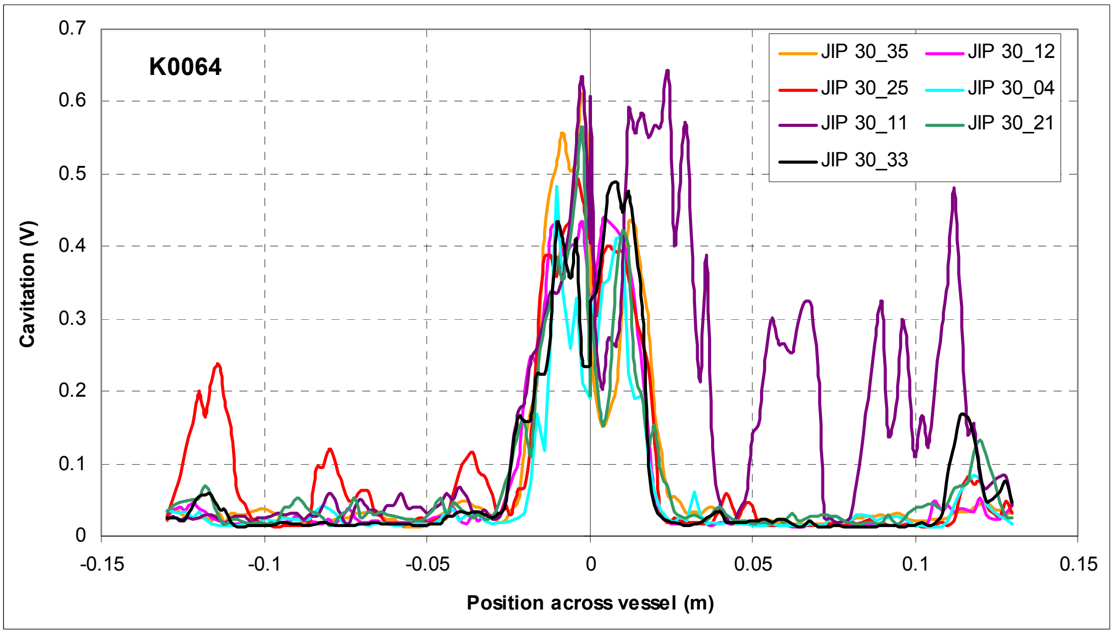


Figure C.2: 100 W scans carried out for Cavimeter K0064 and seven sensors

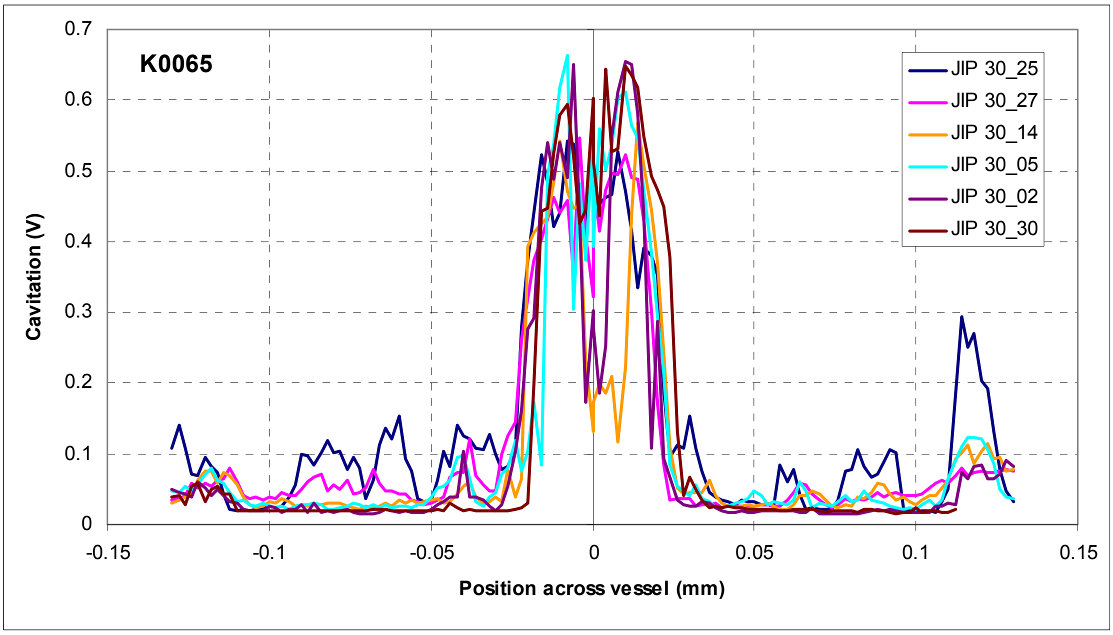


Figure C.3: 100 W scans carried out for Cavimeter K0065 and six sensors

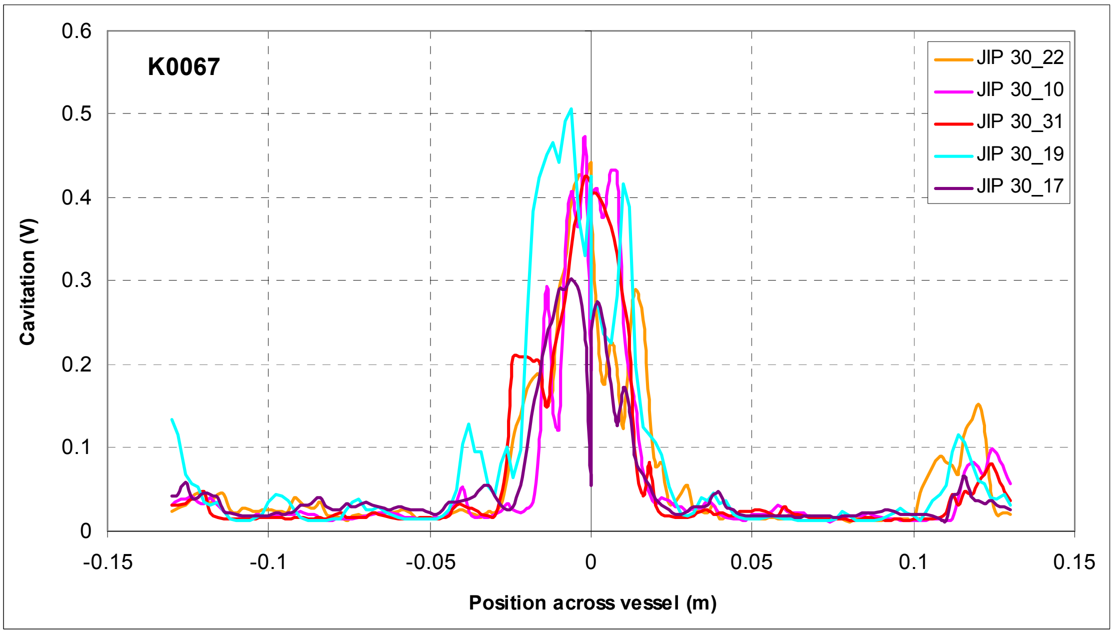
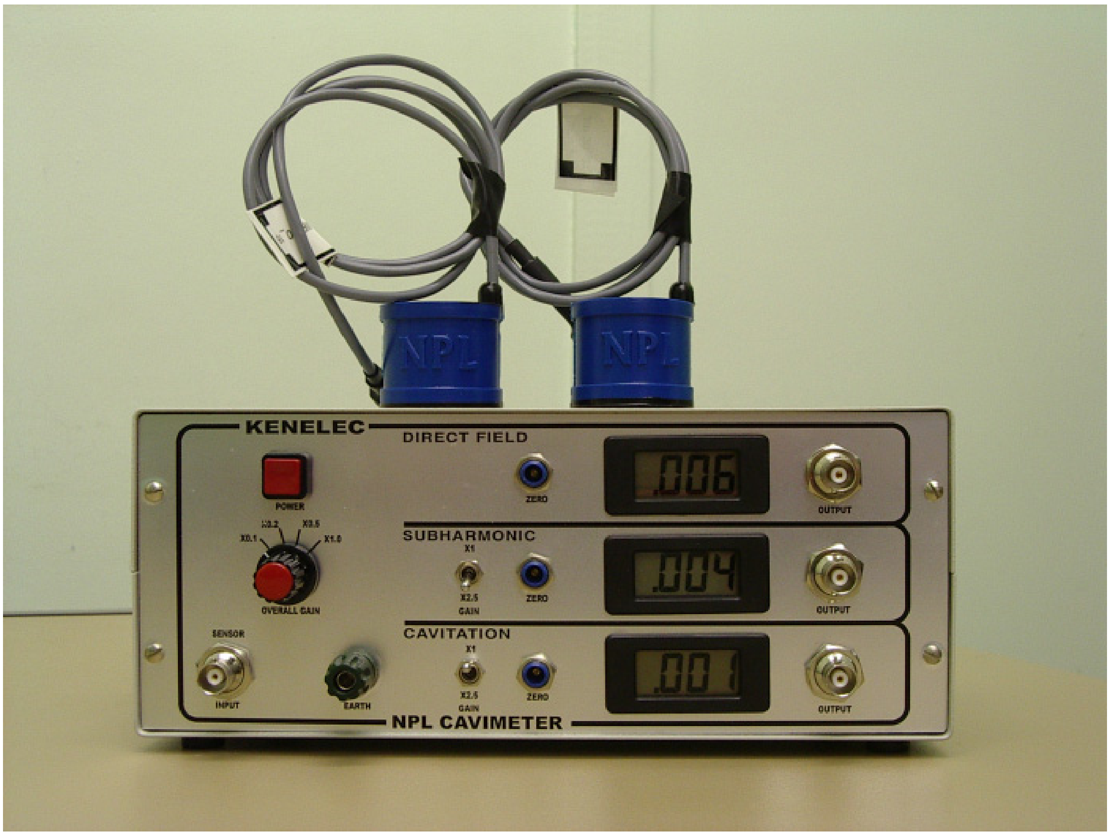


Figure C.4: 100 W scans carried out for Cavimeter K0067 and five sensors

The tests over the four Cavimeters examined in detail showed that generally, consistent cavitation field profiles across the vessel could be generated. However, there are two sensors, JIP 30_25 and JIP 30_11, that showed results that differed from the majority. The first of these was tested using three separate Cavimeters, and it appears that it detects local peaks across the vessel which are not seen by other sensors, and this may mean that is has a smaller detecting area, possibly an extra sensitive region close to the electrode (although this was not seen during the right-angle transducer measurements described in Section 4). Sensor JIP 30_11 shows a significantly different response to all other sensors, and this may be due to electrical pick-up. Consequently, these two sensors were not used in trialling.

APPENDIX D CAVITATION SENSOR AND CAVIMETER USER NOTES



Sensor Type number: **JIP 30**

1 General: Principle of operation of sensor

1.1 The cavitation sensor was developed at NPL as an experimental tool for characterising the acoustic emissions generated by bubbles within liquid media, which are undergoing cavitation (expansion, contraction and collapse in response to a driving acoustic field). The sensing surface of the cavitation sensor, formed by a thin layer of piezo-electrically active membrane material) is a cylinder of internal diameter 30 mm and height 32 mm.

1.2 The primary application of these new sensors is intended to be in characterising the cavitational activity of ultrasonic cleaning vessels. Although these systems typically operate in the frequency range 20 kHz - 60 kHz, the dynamic (nonlinear) bubble processes readily redistribute some of this energy to frequencies of 10 MHz, and even beyond.

1.3 This sensor operates by monitoring these high frequency acoustic emissions. The attached publications provide the rationale behind the way in which the sensor works.

1.4 The cavitation sensor represents an advanced prototype device, and it is provided on an 'as seen' basis. Whilst some testing of the performance of the device has been completed, this has only been carried out over a limited range of conditions, such as temperature, frequency and exclusively aqueous based media. The ability of the sensor to reliably characterise cavitation activity is still, and will continue to be, the subject of on-going research.

1.5 The rubber materials used in the sensor are polyurethane based, and comprise:-

• outer blue cavitation shield material - F37;

Note: The cavitation sensor shield material specification and thickness is such that signals detected above 1.5 MHz can reliably be assumed to originate from acoustic activity occurring inside the sensor volume.

• inner (black) acoustically matched material - F21 - which protects the sensitive electrode from potential cavitation damage.

Health and Safety data sheets for these two materials are available on request.

2 User Instructions - Cavitation Sensor

Practical issues related to the use of the cavitation sensors

The cavitation sensor can be used in two orientations. The first of these is such that its axis of symmetry is perpendicular to the radiating surface of the transducer(s) used to generate the ultrasonic field. That is, the open end of the cylinder should be presented to the radiating surface. This is the recommended orientation for the test and it is anticipated that this configuration will be useful in carrying out 'spot-checks' of activity at set locations within the vessel under test.

2.1 It is also possible to rotate the sensor through 90° relative to the source and record a cavitation signal, although only limited tests have been done at NPL using this configuration. Carrying out measurements in this way clearly reorientates the 'line focus' of the sensor, and, where it has been used, it has proved useful in resolving standing-wave structure, set up between the transducers and the water surface.

2.3 If the transmitting transducer is sufficiently small (for example as would be the case for a sonochemical horn), it can be placed inside the sensor, provided care is taken to avoid direct contact between the source and the sensor.

2.2 For most accurate measurements, the cavitation sensor should be mounted on a rigid rod, which is itself clamped, enabling it to be positioned reproducibly within the acoustic field.

2.3 Testing of the sensor at NPL has been undertaken covering the limited fundamental frequency range of 20 kHz - 49 kHz. Care should be taken if the sensor is used at higher frequencies than these, as the absorption properties of the blue cavitation shield material, may not be appropriate.

Note: the absorption loss within the cavitation shield will increase linearly with frequency, so that it will become increasingly more perturbing to the direct driving field generated by the transducer as the frequency becomes higher.

2.4 Use of solvents will remove the polyurethane shields and render the sensor inoperable. Therefore, the cavitation sensor MUST ONLY BE USED WITHIN AQUEOUS MEDIA.

2.5 At NPL, the sensors have been used over the temperature range 20 °C to 50 °C.

Note: The Curie temperature (the temperature at which the material loses its piezoelectric properties) of the piezo-electric material used within the sensors lies in the range 70 °C to 80 °C.

2.6 Cavitation monitoring is best carried out in a water-surfactant mixture. The inner surface of the cavitation sensor is uneven, and bubbles may develop on the inside of the cylinder when the ultrasonic power is switched ON. This can lead to misleading results. A suitable surfactant is Micro© 90 (International Products Corporation, US). Typically, cavitation measurements at NPL have been made in tap-water with surfactant, in an attempt to mimic the medium which is used within the cleaning industry.

Note: it is useful to observe whether any bubbles are developed on the inside of the sensor during the measurement run. A few small bubbles do not appear to affect results. If bubbles do develop over time, then one effect of this which has been seen is that the high frequency output from the cavitation sensor will increase steadily with time. Sufficient surfactant should de added to suppress the formation of these bubbles.

2.7 Prior to using the cavitation sensor for measurements, it is recommended that it be pre-soaked in a water-surfactant mixture, to ensure that the polyurethane rubber is fully wetted. This should be done for typically at least one or two hours. It may be preferred to leave the sensors soaking for much longer periods - at NPL, the sensors have been left soaking for several days, without any problems caused by water absorption.

Electrical

2.8 The high frequency (MHz) acoustic signals which the sensor monitors are usually at a low level, and steps must be taken to ensure that they are not swamped or compromised by signals arising from electrical interference. Typical noise sources include switched-mode power supplies.

2.9 This can normally be achieved through adequate earthing of the instrumentation, through the use of earth braid, for example.

2.10 If a metallic vessel is used, for example the inner lining of an ultrasonic cleaning vessel, then it is usually very helpful to make an electrical contact between this an the outside of the BNC of the cavitation sensor (which is connected to the Cavimeter input), and then to a clean earth.

2.11 If earthed correctly, electrical noise over the primary frequency range of interest, 1 to 5 MHz, should be negligible.

Note: If a spectrum-analyser is being used, then one should observe the noise floor of the instrument over the frequency range of interest. Whilst it is up to the User to ensure that the effects of any RF pick-up are negligible, there are some useful tips which can be followed. If stepper motors are used to control the position of the sensor within the acoustic field, then it may be necessary to assess whether or not they generate any electrical interference, by measuring the background noise with and without the motors ON and operational. The same is true of the vessel or transducers used to generate the ultrasound. To confirm that there is no electrical component to this - raise the sensor completely out of the water - this should completely extinguish the high frequency component.

The output signal from the cavitation sensor contains many frequency components, in addition to the high frequencies of interest. The largest magnitude component will be generated at the acoustic drive frequency being used (called the fundamental), and, in some circumstances, this may be of sufficient magnitude to saturate any receive electronics, for example if a pre-amplifier is used between the cavitation sensor and the Cavimeter. In such cases, it may be necessary to use an electrical filter or attenuator to reduce the magnitude of the output signal. For this reason, it is recommended that the 0.4 m length cable from the sensor is plugged straight into the input channel of the Cavimeter.

Note: An intervening cable may be used, but it should be noted that this may electrically load the sensor, leading to different sensitivities of the sensor and different readings on the Cavimeter front panel. For the purposes of comparing measurements, it is important that the same electrical loading conditions are applied.

Other components may appear at subharmonic components (fractions of the fundamental) and harmonics (integer multiples of the fundamental). It is therefore recommended to use a spectrum analyser with a bandwidth of at least 10 Hz – 100 MHz to monitor the cavitation sensor signals. To extract the high frequency information, signal averaging may also be required.

3 User Instructions - Cavimeter

3.1 The Cavimeter is designed to be used with the cavitation sensor, and contains processing electronics that filter, amplify and display the broadband signal received from the cavitation sensor in three separate channels. The cavitation sensor output should be connected directly to the Cavimeter input.

3.2 The Cavimeter has an overall input gain control, covering the range x0.1 to x1.0. If during measurements any of the channel displays exceed 1.999, the overall gain control should be adjusted downwards accordingly.

3.3 Direct Field: this channel consists of a low-pass filter and RC circuit, and so displays the time-averaged RMS voltage corresponding to the driving field of the vessel under test (the driving field should always be the strongest component in the received signal). It has a usable bandwidth of 20 – 60 kHz.

3.4 Subharmonic: this channel examines the frequency of the fundamental component, and detects the RMS level of the narrowband signal at half this frequency. In doing so, it effectively ‘tracks’ the fundamental component. It this has a usable bandwidth of 10 – 30 kHz.

Note: Within the technical literature, the sub-harmonic level has been associated with the onset of violent, inertial cavitation; and it has been included in the Cavimeter as it might potentially be a useful parameter regarding cavitation threshold.

3.5 Cavitation: this channel detects the signals in the approximate range 1.5 – 7 MHz produced by bubbles collapsing within the cylindrical volume entrained by the sensor. The front panel display has a fixed 2-second averaging time, and the channel gain is adjustable between x1 and x2.5.

3.6 The Direct Field and Cavitation processing channels include BNC outputs, which carry the filtered signal from the respective channel (without time averaging). These may be connected to an oscilloscope or RMS meter for signal monitoring and PC acquisition. *The subharmonic output BNC should not be used*.

3.7 The electrical performance of the various Cavimeter displays and output Channels has been the subject of extensive testing at NPL to establish the limits of linearity. For most accurate operation, the "Overall Gain" settings of the Cavimeter and the individual "Switchable Gain" settings of the High frequency "Cavitation" Channel and "Subharmonic" Channels (x1 & x2.5), should be set such that front panel displayed value of a particular parameter lies in the range 0.3 to 1.6.

Note: In situations where the cavitation sensor is scanned through the acoustic field, a range of signal values may result, and it is important that the above criteria is not violated. Although the dynamic range of signals will vary according to the characteristics of the vessel, a typical span would be a factor of 2 or 3 in the broadband "Cavitation" signal levels. If the display reading criteria given in 3.7 is met, then both the display and the BNC output will behave linearly.