December 1998

An initial review of transducers and calibration methods suitable for airborne ultrasound measurement standards

Karen Smart
Centre for Mechanical and Acoustical Metrology
National Physical Laboratory
Teddington
Middlesex
United Kingdom
TW11 0LW

ABSTRACT

NPL's current measurement standards for airborne sound extend to 50 kHz and are realised through the free-field calibration of IEC type LS2 microphones. However applications using sound in air at frequencies well beyond our limit of hearing and beyond 50 kHz are increasing. With this comes the possibility of hazardous exposure. Published guidelines on what is and is not safe are minimal. However, even before these can be set the ability to make reliable measurements at ultrasonic frequencies needs to be established. This report describes a series of measurements that have been made to examine the feasibility of extending the capability of the NPL free-field reciprocity calibration facility. It investigates the current limitations on measurements at higher frequencies and considers alternative transducers on which the measurements could be based. The measurements that have been made extend to 200 kHz.

ISSN 1369-6785

National Physical Laboratory,
Teddington, Middlesex, UK, TW11 0LW.

Approved on behalf of Managing Director, NPL,
by Dr G R Torr, Head, Centre for Mechanical and Acoustical Metrology.

CONTENTS

1. INTRODUCTION

A principal reason for needing to measure sound is the damaging effect it can have on our hearing. Increasingly it is becoming necessary to make measurements beyond the normally accepted upper frequency limit of around 20 kHz, because of the range of sources that generate airborne sound above this frequency that have emerged. Even though sound at these frequencies develops no sensation of hearing, there is still potential for damage if the sound pressure is at a sufficiently high level.

Before reliable measurements of airborne ultrasound can be made, it is important that primary standards be developed beyond the current limit of 50 kHz. The work described in this report focuses on the potential for extending NPL's current measurement standards up to 200 kHz since this is the range utilised by many of the currently developed technologies. However it is recognised that primary standards may well be required up to a few megahertz to adequately cover the range of future applications. Only when a primary standard, and a method of calibrating measuring devices, has been established can the damaging effect of airborne ultrasound be quantified and legislation to limit exposure be put in place.

1.1 AIRBORNE ULTRASOUND SOURCES

Applications where airborne ultrasound is a concern can be categorised into two groups; those where the ultrasound is produced as a by-product of some other process and those that produce the ultrasound intentionally. Both types of applications present the same potential problems.

Examples of widespread industrial applications that produce airborne ultrasound include welding and cleaning. In both cases ultrasonic transducers are used to create high levels of sound energy in a medium other than air (usually water), which subsequently passes into the air. It is often very noticeable that sound is propagating in the air and some level of noise exposure is experienced by the operator. Effects such as audible popping and crackling have been reported, together with subjective and physiological effects after even brief exposure. This is perhaps a cause for concern since studies have suggested that when audible components are present with ultrasound, the risk to the subject is increased.

An everyday example of airborne ultrasound that is produced intentionally is in range finders used in applications which include from helping cameras to focus and allowing robots to 'see'. Taken one step further, beams of ultrasound can be used to monitor movement. An example of this is a device that has been developed to monitor the movement of a baby's chest as it breathes. This has been used to monitor babies thought to have increased risk of sudden infant death syndrome as they sleep.

A recently developed technical application is the parametric array[1], which is used to produce highly directional low-frequency sound. Reports have appeared describing arrays capable of beaming a signal over 200 m. This has been achieved following development of transducers capable of generating very high signal levels at the array source.

There is an emerging commercial application of similar technology, which if suitably developed could end up in our homes. It is a sound generation system for public spaces. The aim is to generate audible sound above an audience by the interaction of two ultrasound beams. The proponents of such devices claim that the sound will be purer and steerable (so that the apparent source of the sound can be moved around the space), but the systems rely on generating high intensity ultrasound beams at 200 kHz above the heads of an audience.

This is just a small selection of examples. Others include the use of ultrasound to speed the process of food dehydration, in sonochemistry to process polymers, to improve dying processes in the textile industry and in the removal of fine pollutants from water and gases. The range of applications, the frequency range and the power utilised are expanding all the time.

1.2. PHYSIOLOGICAL ASPECTS OF ULTRASOUND

In the early 1950s, as industrial applications of ultrasound began to develop, reports appeared of the effect of ultrasound exposure on humans. Crawford[2] reported that laboratory workers in the UK had suffered unusual fatigue, loss of equilibrium, nausea and headaches which persisted after the exposure had ceased and 'some loss of hearing in the upper audible frequencies'. Complaints of fatigue, headaches, nausea and temporary tinnitus among workers using ultrasonic devices in industrial production have been reported by Acton and Carson[3] and others. These observations led to investigations of the possible effects of exposure to airborne ultrasound on hearing and the development of exposure criteria[4].

1.3. PRESENT LEGISLATION FOR NOISE AND ULTRASOUND EXPOSURE

Noise exposure is governed in the UK by the Noise at Work Regulations 1989[5] which are based on EC directive 86/188/EEC[6]. These regulations define two action levels. The first can be considered as the maximum desirable level that should exist in the workplace and the second sets the level where employers are legally obliged to take action to prevent exposure. These limits are 85 and 90 dB A-weighted continuous equivalent sound pressure level (L_{eq}) measurements based on an eight hour period and measured in the frequency range 20 Hz to 20 kHz. The directive does not contain any requirements for exposure to acoustic pressure at frequencies beyond 20 kHz.

Internationally, some guidelines for exposure to airborne ultrasound between 20 and 100 kHz do exist. They were established using data collected between 1960 and 1981[7,8,9], and published by various international organisations. There is no guidance for frequencies over 100 kHz.

1.4. REQUIREMENTS FOR TRACEABILITY AT HIGHER FREQUENCIES

The existence of guidelines on exposure limits are of little use if it is not possible to make reliable measurements against them. Moreover it is arguable that the ability to make traceable measurements is essential to determine damage criteria and formulate the guidelines in the first instance. In addition, accurate measurement of industrial noise levels is of vital importance to the audiological health of workers. All of these issues rely on the foundation of a primary standard. In the audible frequency range this is realised through the calibration of laboratory standard microphones using the pressure reciprocity method[10], but this does not extend beyond 20 kHz.

It is also possible to calibrate IEC type LS2 microphones up to 50 kHz using the free-field reciprocity method[11]. Beyond this frequency the sensitivity of such microphones reduces rapidly making further extension impractical but this report investigates the use of alternative transducers, including smaller microphones having higher roll-off frequencies which could form the basis of a primary standard at higher frequencies.

2. MEASUREMENTS ABOVE 50 kHz USING THE NPL FREE-FIELD FACILITY

The free-field reciprocity calibration facility at NPL enables IEC type LS2 microphones to be calibrated up to 50 kHz. The method requires two microphones to be coupled in a free-field chamber. One microphone is driven with an electrical current i and is used a transmitter. The sound waves that result produce a pressure at the second microphone, resulting in an open-circuit output voltage U. The method requires a measure of the electrical transfer impedance (U/i) to be combined with the theoretical acoustical transfer impedance, to give the sensitivity product of the two microphones. The modulus of the sensitivity product is given by

$$\left|M_1 M_2\right| = \frac{2d}{\rho_0 f} e^{-\alpha d}\left(\frac{U}{i}\right) \quad (1)$$

where d is the distance between the two microphones, α is the sound absorption coefficient in air, ρ_0 is the density of the air and f is the sound frequency.

The measurement of U/i is made by allowing the transmitter current to pass to ground through one arm of a π-network of resistors, while the transfer impedance of the network is adjusted so that the microphone output voltage is developed across the other arm. Under these conditions U/i is given by the transfer impedance of the network[12]. The method used is automated and does not require the π-network impedance to match U/i exactly. It is possible to balance the system approximately, compensating for the mismatch by measuring voltage ratios within the system.

Two points should be noted that limit the practical implementation of this method. The first is that the distance d is the separation between the two point sources equivalent to the microphones, which is typically not the same as the physical separation. The position of these point sources relative the microphone diaphragm is known as the acoustic centre and needs to be determined in the calibration procedure. The second complication is that the output voltage U is very small and limited by the response of the transducers used.

It is this last point that limits the frequency range of IEC type LS2 microphones. IEC type WS3 and type WS4 microphones have the potential to extend the range to 125 kHz and 200 kHz respectively, but the low signal level becomes increasingly difficult to resolve. A recent study[13] identified potential alternative transducers. One was an electrostatic type device used in cameras as a range finder. The second used micro-machining technology to construct a number of miniature transducers in the form of an array on a single structure. Unfortunately it was not possible to test an example of this last transducer in this study.

2.1 MEASUREMENTS WITH IEC TYPE WS3 MICROPHONES

The first step towards extending the frequency range of the measurements was to use IEC type WS3 microphones. The Brüel and Kjær type 4135 is a WS3F microphone that has a nominally higher sensitivity than the equivalent WS3P, so this was the obvious choice with which to begin measurements. The feasibility of using these devices was tested by measuring U/i as a function of distance for a pair of microphones. From equation (1) a quantity y was calculated as in equation (2).

$$y = \frac{\rho_0 f}{\frac{U}{i}} \quad (2)$$

If y is then plotted as a function of the physical separation d', a straight line graph is expected where the gradient gives the reciprocal of the sensitivity product and the intercept on the d' axis allows the acoustic centre to be derived[12]. All of the investigations described in the report are limited to this type of measurement as this forms the basis of the complete calibration procedure. If this measurement proves to be feasible, resulting in a straight line graph, then full calibration should be an easy step to take.

An adapter was used to mount the microphones on the preamplifiers in the free-field chamber and the measurements were made with the microphone grids removed. It was soon found that the B&K type 4135 microphones selected were unsuitable because of the level of noise produced. This was probably due one of the microphones being faulty. Measurement therefore had to proceed with a pair of B&K type 4136 (WS3P) microphones. Although these had a slightly lower sensitivity, the measurements were much more reproducible. Figure 1 shows a typical result at 40 kHz. The units of y are (m Pa^2)/V^2. Unfortunately these microphones are designed to have a flat pressure response so like WS2P microphones there comes a point in the frequency range where their sensitivity starts to decrease. The highest frequency where these microphone could be used was found to be 63 kHz. The frequency response of B&K type 4135 microphones is designed to be flatter to a higher frequency. In theory, these microphones could be used to around 125 kHz, but this has not been attempted. However this probably represents the extent of the potential for using WS3 microphones.

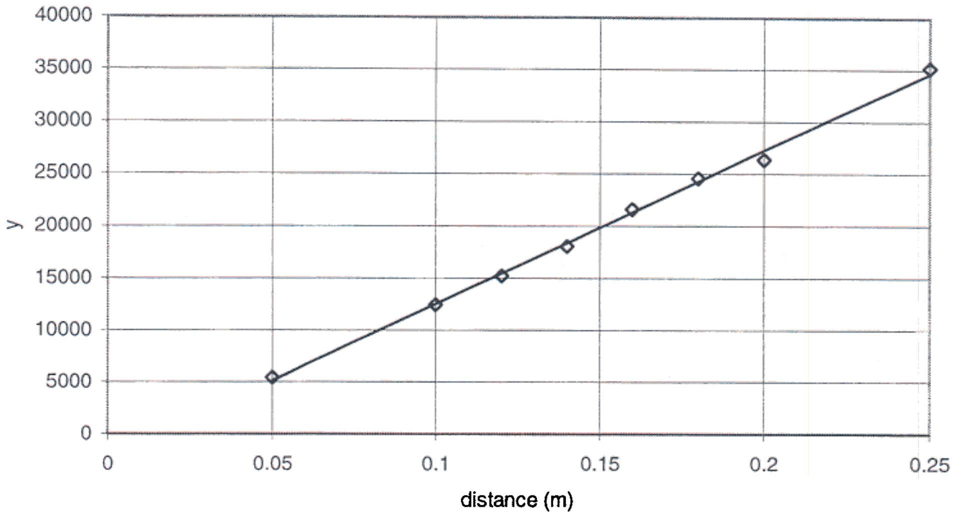

Figure 1 Results for a pair of B&K type 4136 microphones at 40 kHz.

The use of WS3 microphones and the frequency range in which they were being operated caused the automated facility to select impedance settings not normally used in the calibration of LS2 microphones. So to test the validity of the results obtained, some measurements were performed to examine the effect of using a π-network with a transfer impedance either higher or lower than the optimal one. This caused a wider range of settings to be exercised and tested the validity of the calculated transfer impedance of the π–network. The results of these measurements are shown in Figures 2 to 4.

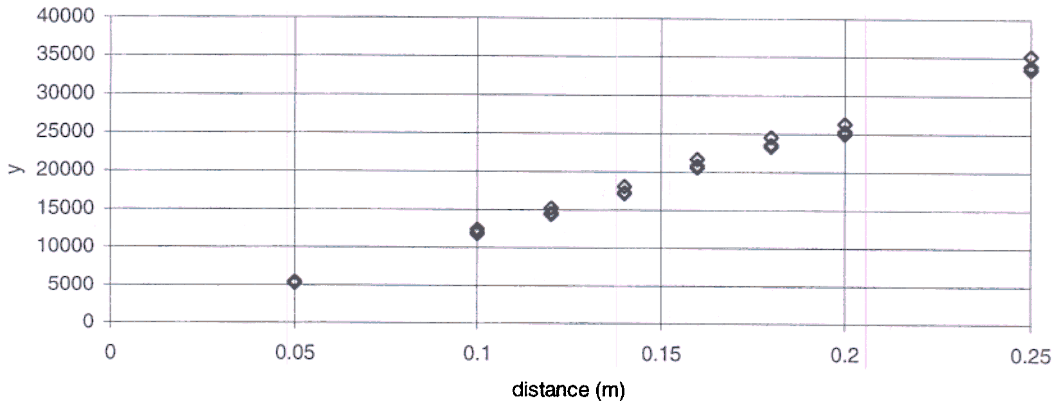

Figure 2 Results for 4136 microphones at 40 kHz, using three different resistors to balance the system at each measurement distance.

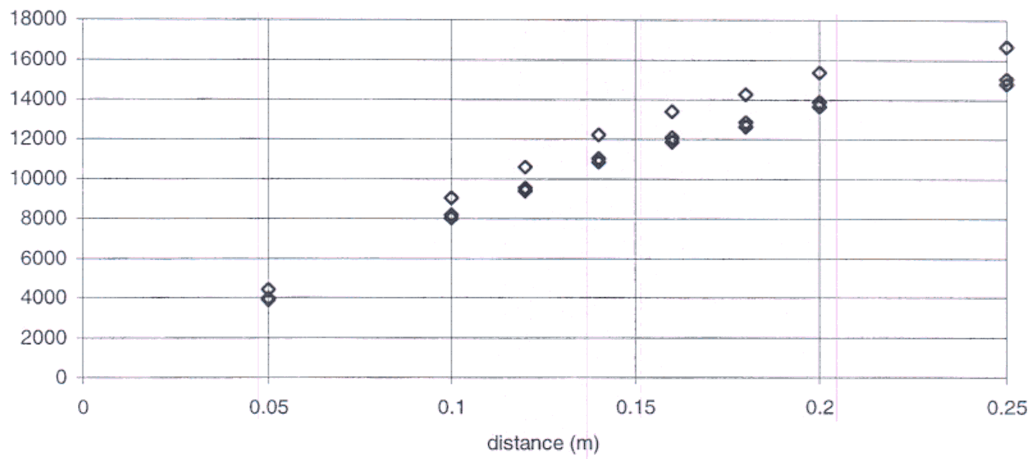

Figure 3 Results for 4136 microphones at 50 kHz, using three different resistors to balance the system at each measurement distance.

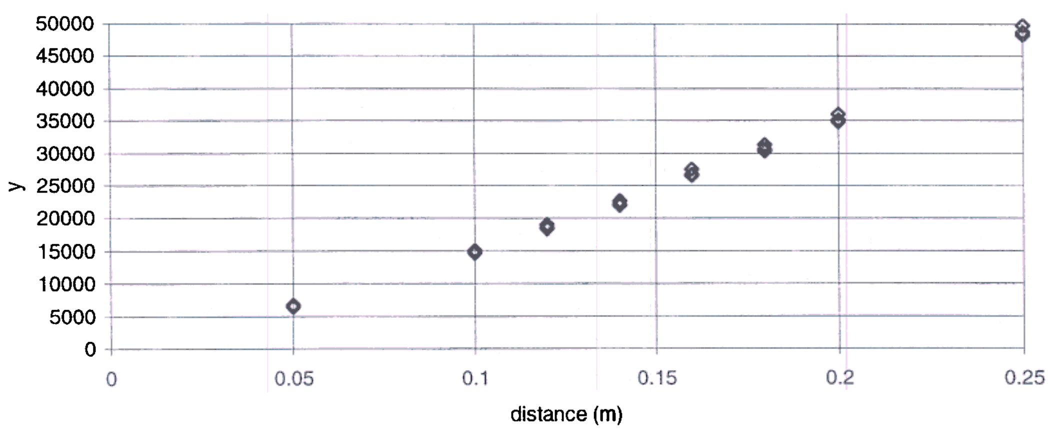

Figure 4 Results for 4136 microphones at 63 kHz, using three different resistors to balance the system at each measurement distance.

At first sight these results are quite encouraging. There is quite good agreement between measurements with different resistor networks and the lines, although not perfectly straight, do fit reasonably well to straight lines. However, closer inspection shows that if the data is extrapolated towards the origin, the intercept value on the distance axis is a few centimetres, when a value around 1-2 mm might be expected. The reason for this was not discovered, but later developments were to eliminate this characteristic.

2.2. MEASUREMENTS WITH POLAROID TRANSDUCERS AT 200 kHz

Before looking at suitable transducers to operate at 200 kHz, there were limitations of the calibration facility that needed to be addressed. The first was that the operating frequency of the lock-in amplifiers extended to only 120 kHz, so these were replaced by Brüel and Kjær measuring amplifiers type 2610. A filter type 1617 was also used in the receiver channel. This has an upper operating frequency of 160 kHz so, a Krohn Hite filter type 3944 was also used to extend the measurements to 200 kHz.

Examples of common airborne ultrasound transducers used in everyday products are those produced by Polaroid (see Figure 5). The device chosen to examine the performance of the system at 200 kHz was the Polaroid K-type transducer. This is a piezoelectric transducer that, according to the data sheet, has a suitable output at 200 kHz. However this is only achieved by it having a strongly resonant behaviour.

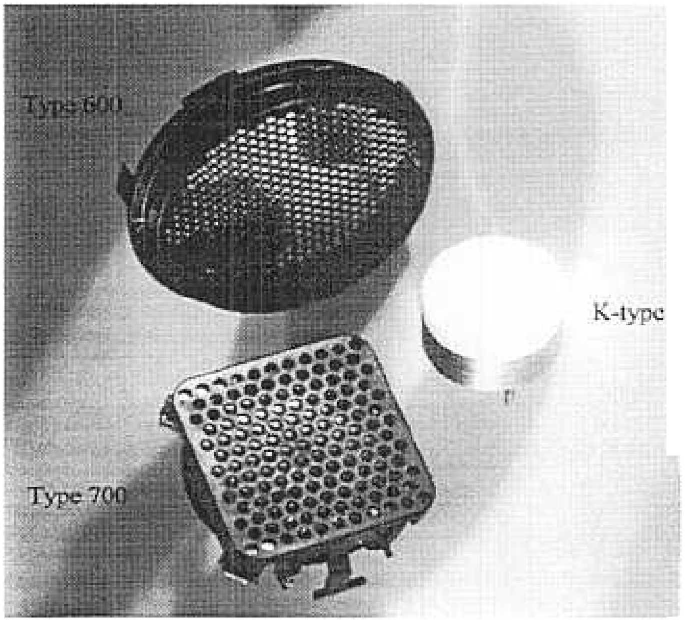

Figure 5 Some ultrasound transducers designed for use in air

2.2.1. Measurements using a π-network as the current sensor

One reservation was whether such transducers could be considered reciprocal, so initially IEC type WS4 microphones were also considered. These have a very low sensitivity which immediately prevents a pair of them from being used together for reciprocity calibration with the typical microphone separations used in the NPL chamber. However measurements with a WS4 microphone (Brüel and Kjær type 4138) and the Polaroid K-type transducer were made. The use of type 4138 as the transmitter had to be avoided because it produces very little output resulting in poor signal-to-noise ratio. Figure 6 shows the results obtained using four alternative π-networks.

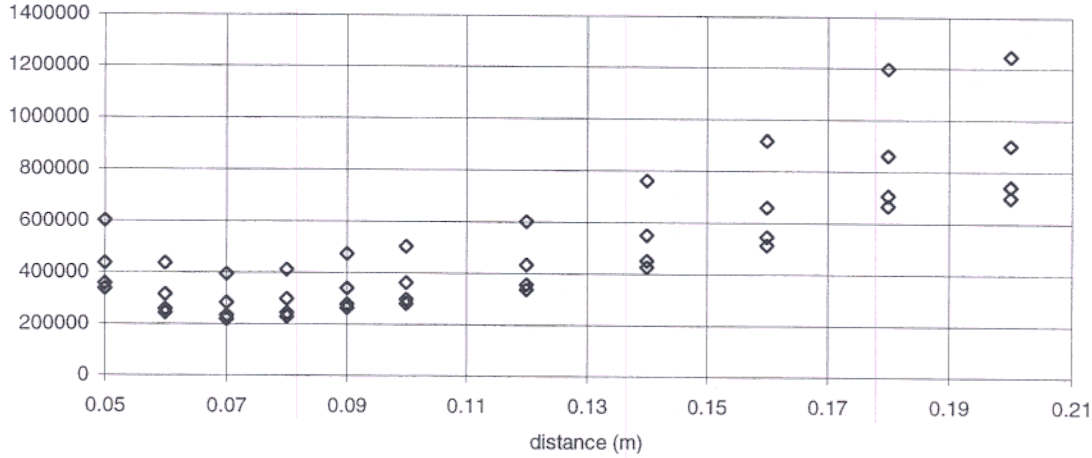

Figure 6 Results for Polaroid K-type transducer (transmitter) and type 4138 microphone (receiver) at 200 kHz using four different resistor networks.

These results show a deviation from the expected behaviour when the transducer separation is less than 0.1 m. This is thought to be due to near-field effects of the 19 mm diameter Polaroid transducer. They also show some discrepancies between measurements with the four different π-networks which were thought to be due to the effect of stray reactive elements contained in the π–network.

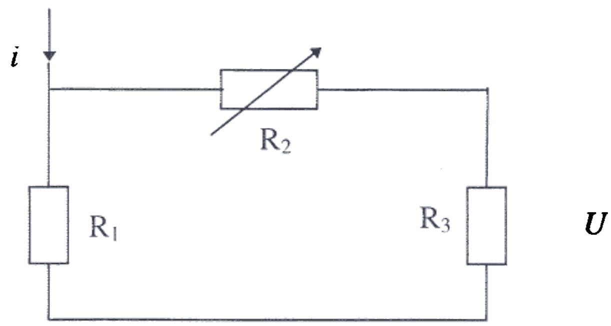

Figure 7 The resistor π-network

Figure 7 shows the form of the π-network used. The transfer impedance of each network is calculated from the d.c. resistance of each component. Clearly any reactive elements present in the network can have a significant influence on the transfer impedance that results in practice. To investigate the presence of unwanted reactive elements, such as stray capacitance, the frequency response of each network was analysed. The results clearly indicated that at frequencies above 50 kHz the influence of stray impedance on the higher value resistors was likely to affect the measurements and so an alternative means of measuring U/i was required.

2.2.2. Measurements using a current probe as the current sensor

Hydrophones are calibrated in water at frequencies up to 500 kHz using the reciprocity method. This application uses a probe method to measure the transmitter current. Essentially the probe consists of an inductive coil that is placed around the cable driving the transmitter, allowing the current to be deduced from the induced voltage and magnetic field strength. This method was adopted into the free-field reciprocity facility to continue with these high frequency measurements.

The revised measuring system is shown in Figure 8 and was first tested using a pair of another type of Polaroid transducer, the type 700. This is an electrostatic device that combines the benefits of a greater output compared with WS3 microphones and a much smoother frequency response than the K-type transducer used earlier. Although it is specified for use at around 60 kHz, it still provides a suitable output level at 200 kHz.

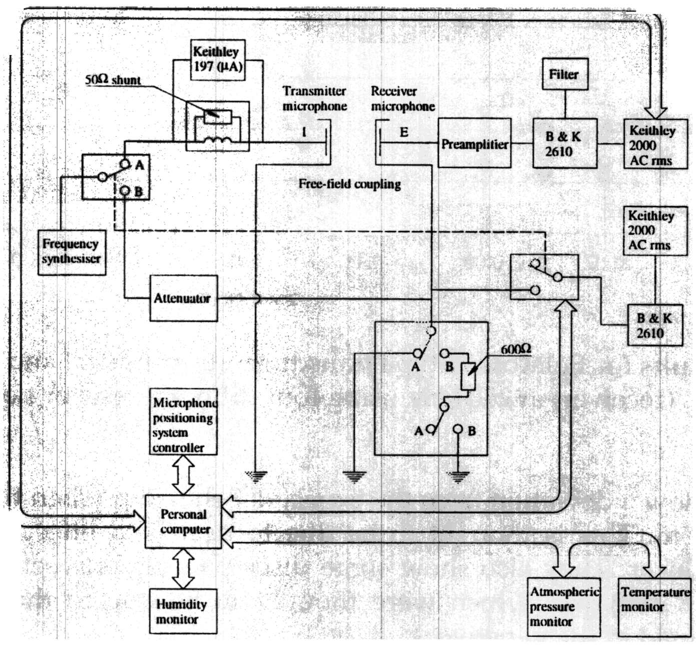

Figure 8 Revised measuring system.

A series of measurements were conducted to investigate the reciprocal nature of the Polaroid type 700 transducers. The transducer was paired with a type 4136 microphone and sets of measurements were made with the role of each transducer reversed. The results are shown in Figure 9 and Figure 10.

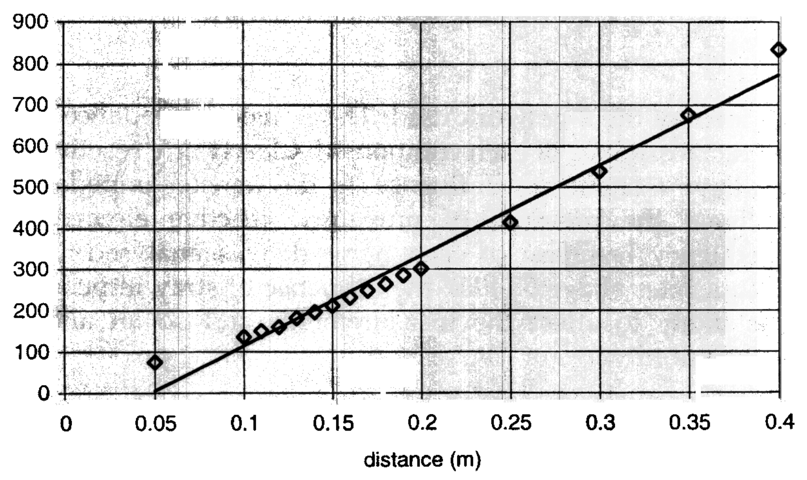

Figure 9 Results for a Polaroid type 700 (transmitter) and B&K type 4136 (receiver) at 63 kHz.

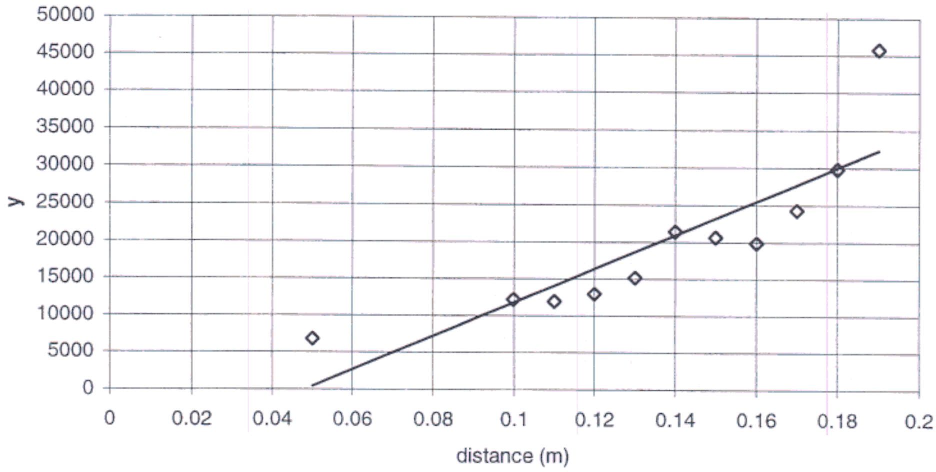

Figure 10 Results for a B&K type 4136 (transmitter) and Polaroid type 700 (receiver) at 63 kHz.

These results are clearly very different. It could be that the reduced signal level produced by the microphone when used as the transmitter has resulted in a higher signal-to-noise ratio. The larger size of the Polaroid transducer could also be influencing the field in different ways depending on its location. Certainly there is some deviation from free-field behaviour in both cases. This is evident from the curvature in the form of the data which is slight in Figure 9, but more pronounced in Figure 10. From the form of these two graphs it is obvious that the Polaroid transducer is not reciprocal and this was confirmed by other measurements.

As an experiment, a pair of Polaroid type 700 transducers were then used together. The results are shown in Figure 11. Now the form of the graph is more like what would be expected. Although the data points are scattered about the best fit line, this is not unusual in free-field measurements at these very high frequencies in the early stages of development. However because the devices are not reciprocal their use in implementing the reciprocity method is limited.

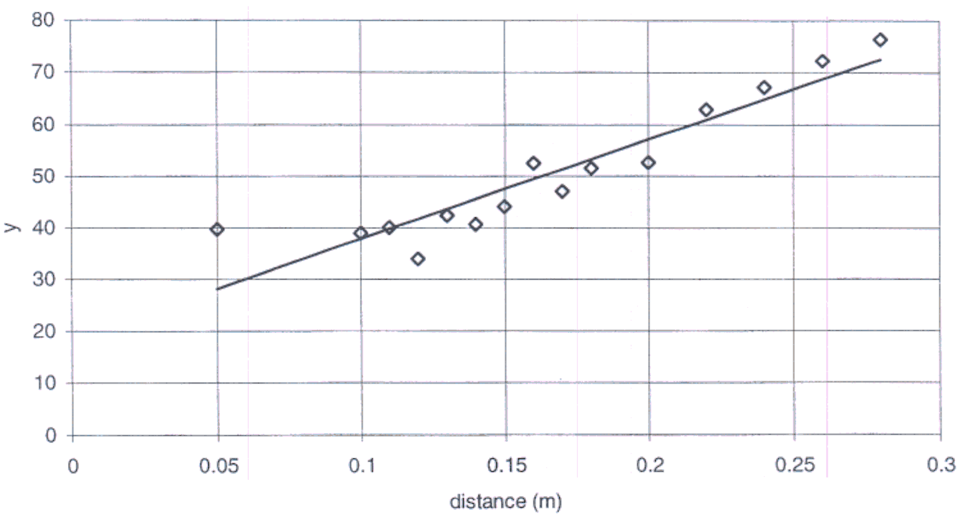

Figure 11 Results for a pair of Polaroid type 700 transducers at 63 kHz.

The final investigation that was made with the revised facility was to repeat the measurement using the B&K 4136 microphones. The results are shown in Figure 12.

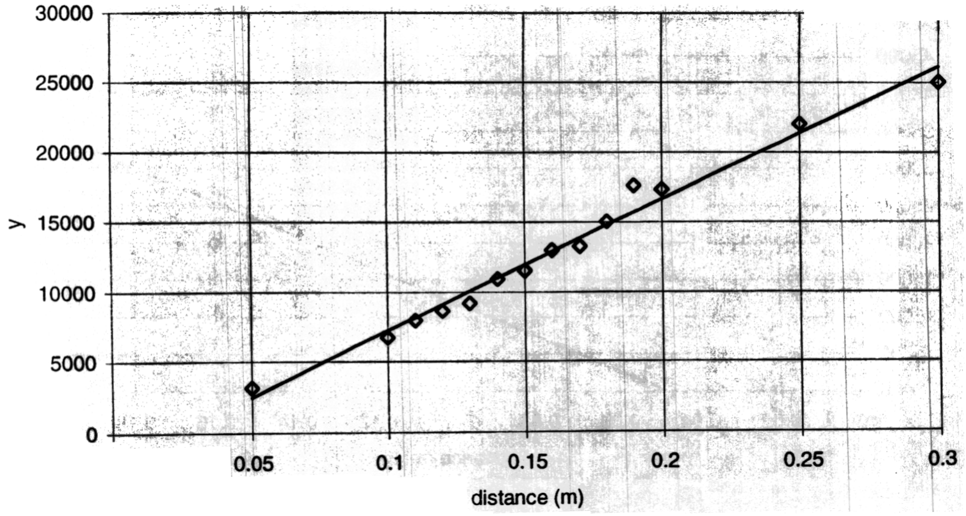

Figure 12 Results for a pair of B&K 4136 microphones at 63 kHz.

3. DISCUSSION OF RESULTS

The measurements described have highlighted a number of important issues related to the transducers and to the acoustical and electrical environments used for the tests.

The results obtained with the WS3 microphones are encouraging. Even though there is a fundamental frequency limit to their use, they can provide a useful and relatively straight forward extension to the present capability. The extent of this will be governed by the suitability of WS3F microphones like the B&K type 4135 microphone used without success early in these tests. It needs to be ascertained whether this was due to the particular microphones used or a characteristic of the microphone type. WS3F microphones are usually designed to have more damping of the diaphragm movement compared to WS3P microphones. The poor performance of WS3F microphones observed in the measurement may or may not be related to this property.

The other transducers were also used with varying degrees of success. The piezoelectric Polaroid K-type proved difficult to use, perhaps because of its resonant characteristics. The Polaroid type 700 gave better results, particularly when its function was limited to use as a transmitter. The drawback with both these devices was their size. Both are likely to influence the acoustic field in different ways depending on the orientation in which they are mounted. The limited information on the directivity patterns produced by these devices that was available, show they would not act as point sources. Furthermore the results that have been obtained indicate that the devices are not reciprocal. While these transducers were useful for this study, being readily available, they are not suited to this type of application.

Extending the frequency range of the facility has highlighted the limitations of the resistor π-networks as a means of traceability. Measurements have shown that the key resistor in the network, R_2, can be significantly influenced by stray elements when the frequency is raised. The detailed analysis of these networks has not been discussed in this report, but it showed that two elements, a capacitance and an inductance, have an effect on R_2. If these elements can be quantified, then it is possible to calculate the complex impedance of the network at a given frequency. However the analysis so far, indicates that these elements change with frequency, making such an approach impractical.

The alternative approach using the current probe was shown to produce equivalent results. This device has the potential to operate to higher frequencies than this study is concerned with. However, as with any newly developed measuring system, it suffered initial problems. With further development within the facility, the current probe has the potential to produce reliable results in the future.

Some of the results obtained have shown a slight but regular deviation from the straight-line behaviour expected. This is illustrated well in Figure 9. The reason for this is likely to be acoustical in origin. In particular, the air attenuation becomes important at these elevated frequencies. It is therefore very important to be able to measure the environmental properties of the air, to enable the attenuation to be calculated correctly. The deviation that can be seen in the data causes the acoustic centre derived from the graphs to be significantly over-estimated. Greater attention to these factors, to match the demands of working at higher frequencies, is needed to improve the results in this area.

4. RECOMMENDATIONS

This report has described measurements that were intended as a first look at the issues involved in extending the NPL free-field reciprocity facility. Further work must be undertaken if measurement standards at frequencies above 50 kHz are to be developed. The following conclusions and recommendations can be made as a result of the work so far.

- None of the transducers considered have proved suitable for use up to 200 kHz. However, the search for such a device should continue.
- Stray impedance limits the use of the π-networks above 50 kHz. The use of the current probe should be developed further to provide a means of testing any new transducers above this frequency.
- Research should be broadened to consider other possible calibration techniques, perhaps capable of measuring at even higher frequencies than considered in this report.

5. REFERENCES

1 Thomas D. Kite, John T. Post, and Mark F. Hamilton. *Parametric Array in Air: Distortion Reduction by Pre-processing.* The ICA/ASA Proceedings, Seattle WA, June 1998.

2 Crawford A E 1955, *Ultrasonic Engineering*. Butterworth, London.

3 Acton W I and Carson M B, 1967. Auditory and subjective effects of airborne noise from industrial ultrasonic sources. *British Journal of Industrial Medicine* **24**, 297.

4 International Non-Ionising Radiation Committee of the International Radiation Protection Association. *Interim Guidelines on the limits of Human Exposure to airborne ultrasound.* Health Physics **46**, 969-974

5 The Noise at Work Regulations 1989, SI 1989 No. 1790, HMSO

6 European Community Directive, on the protection of workers from risks related to exposure to noise at work Council Directive No. 86/188/EEC (1986).

7 Health Canada. Guidelines for safe use of ultrasound: Part II - Industrial and Commercial Applications Safety Code 24, ISBN 0-660-13741-0.

8 Ultrasound Environmental Health criteria **22**, World Health Organisation, Geneva, 1981.

9 Non-ionizing Radiation Protection World Health Organisation, Regional Publication European Series no. **10**

10 IEC 1094-2:1992, Measurement Microphones - Part 2: Primary method for pressure calibration of laboratory standard microphones by the reciprocity technique.

11 IEC 1094-2:1992, Measurement Microphones - Part 3: Primary method for free-field calibration of laboratory standard microphones by the reciprocity technique.

12 R G Barham 1995, Free-field reciprocity calibration of laboratory standard

microphones. Ph.D. thesis, ISVR, University of Southampton.

13 Duncan Jarvis, Peter C M Galloway, Hilary McNeill 1996. Future Transducer Technology Advances in Acoustics- a Strategy for the UK National Measurement System. NPL Report CIRA(EXT) **014**.