

**Measurement of the
Surface Displacement in
1-3 Piezo-composites**

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Measurement of the Surface Displacement in 1-3 Piezo-composites

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ABSTRACT

Two methods for measuring the out-of-plane displacements of a range of 1-3 piezo-composites have been investigated. The first uses a surface profilometer to scan the surface profile of 1-3 piezo-composites under static DC conditions. The second uses a laser Doppler vibrometer to record the dynamic surface displacement profile of the composites at various frequencies and electrical actuation drive level. Regions of composite that have lower than average piezoelectric element density exhibit a reduced overall displacement compared to regions that are more densely packed with piezoelectric phase. This is expected and the manner in which matrix and piezo-rod or fibre interacts, especially near the matrix fibre interface, as a function of frequency and voltage is discussed. The methods have been compared and ways in which the data may be visualised for greater understanding of the effect of composition, volume fraction, aspect ratio etc. have been explored.

CONTENTS

1	INTRODUCTION.....	1
2	EXPERIMENTAL METHODS.....	4
2.1	SURFACE PROFILOMETER – STATIC OR DC TECHNIQUE.....	5
2.2	LASER DOPPLER VIBROMETRY – AC TECHNIQUE.....	6
3	EXPERIMENTAL RESULTS AND DISCUSSION.....	8
3.1	STATIC SYSTEM – UBM SURFACE PROFILOMETER.....	8
3.2	DYNAMIC SYSTEM – DOPPLER LASER VIBROMETER.....	12
4	CONCLUSIONS.....	20
5	REFERENCES.....	20
6	ACKNOWLEDGEMENTS.....	21

1 INTRODUCTION

Piezo-composites are used extensively for hydrophone and medical transducer applications [1-7]. This is because of the composite's inherently high electromechanical coupling coefficient and broad bandwidth [3,7]. A higher sensitivity compared to its bulk piezoelectric ceramic constituent and broad bandwidth is attributed to the lower acoustic impedance and its higher coupling factor. The increased level of thickness-mode electromechanical coupling (k_{33}) for piezocomposites compared to their monolithic equivalent is achieved because the lateral clamping of the ceramic elements is partially released in the composite structure [8]. Transducers made from monolithic materials suffer poor efficiencies due to energy absorbing backing pieces that are added to increase device bandwidth. Other areas of application for piezocomposite devices include ultrasonic non-destructive testing (NDT), flaw detection, thickness measurement, diagnostic imaging, multibeam ocean survey transducers, acoustic communications, ink-jet print heads, optical positioning and in-process quality control.

The hydrostatic performance of a typical piezoelectric ceramic is central to its use as an underwater transducer. Under these conditions the piezoelectric response is a summation of the resolved components parallel and perpendicular to the poled direction (pressure exerted on all faces of the ceramic), and we can write down the total piezoelectric coefficient as $d_h = d_{33} + 2d_{31}$ (for poled polycrystalline ceramic such as PZT (∞mm)). Even though d_{33} and $-d_{31}$ are both quite large (315 and -135 pC/N respectively for PZT4D composition. Morgan Electroceramics) the summation of the positive d_{33} with twice the negative d_{31} coefficients yields a low value of d_h (45 pC/N in this example). Additionally, because the permittivity ϵ_{33}^T is fairly high for many compositions then the piezoelectric voltage coefficient $g_h = d_h / \epsilon_{33}^T$ is also low, resulting in a transducer with low sensitivity.

These issues led to the development of the piezocomposite, since by combining piezo-elements in a polymer matrix it was possible to increase the magnitude of d_h and g_h . The nomenclature describing such composites classifies their microstructural connectivity [9]. The first number refers to the connectivity of the active or piezoelectric phase and the second number refers to the matrix phase. The numbers range from 0 to 3 each signifying their respective spatial dimension. For example a 1-3 composite has piezo phase self-connected in one dimension and the '3' means the matrix is self-connected throughout the composite. Further classifications may refer to additional phases being present. For example, the 1-1-3 composites have, in addition to the aligned piezo 'rods' in its polymer matrix, a coating or interphase between piezo rod and matrix. In fact, such composites have been shown to possess superior properties over 1-3 composites [10].

The key attribute of the 1-3 piezocomposite that dominates its hydrostatic performance is its high piezoelectric coupling factor. The composite nature of the structure is key to understanding why these devices have such a high coupling factor. The volume average of the stress induced electrical displacement is dependent on the summation of the axial stress in the fibre and the lateral stress transferred from the surrounding matrix. Since the load transfer laterally is highly reduced and damped (from the compliant matrix) then the average contribution to the d_h from d_{31} of the fibres is reduced and the transducer exhibits higher values of hydrostatic piezoelectric coefficient. The most important design parameter for 1-3 composites is to maximise the materials coupling coefficient. The thickness mode coupling of the pure ceramic is usually much lower than the composite because the ceramic is stiffly coupled in all directions and energy is transmitted in 3 dimensions, whereas 1-3 piezo-

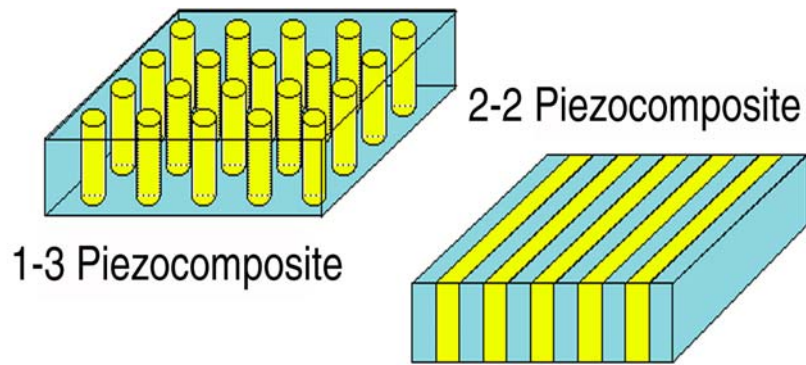


Figure 1: Schematic showing structure of two types of Piezocomposite

composites transmits and receives largely in only one dimension [3]. Since the electromechanical efficiency of piezo materials is approximately proportional to the square of the coupling coefficient then the efficiency of piezo composites is almost twice that of the piezoceramic from which it is made.

The added advantage of composite structure design is the reduction in acoustic impedance that can occur to one that more closely matches many liquids such as water and solids such as organic tissue. Thus, for underwater applications or medical ultrasonic applications, there is less energy reflected at the interface between transducer and medium and hence higher efficiency devices are realised.

A typical 1-3 piezocomposite is shown in figure 1, and consists of a regular array of piezoceramic rods or columns embedded in a polymer (epoxy) matrix, electroded both ends and poled in conventional ways. The composites are fabricated using a variety of techniques including, dice and fill, where a block of piezoelectric ceramic is diced in the X and then the Y direction to render an array of closely spaced columns that are then infilled with a thermoset (or other) polymer material. Alternatively the composites are made using more cost effective methods (and with less wastage) such as injection moulding.

For more information of processing and manufacturing please refer to the various manufacturers web sites:

www.smart-material.com, www.blatek.com, <http://www.matsysinc.com/>, www.vermon.com, www.sei.co.jp/sn/97_20.html

Piezo-composites are characterised in many ways. Following any microstructural characterisation, such as SEM, optical microscopy, cross sectional SEM/TEM, XRD, acoustic microscopy, c-scan, acoustic emission, etc, the device may be electrically investigated. Although the device is considered broadband, it still exhibits resonant behaviour due to the coupling between its piezoelectric response and its physical dimensions to the driving field. Typically, for small composites these resonance's occur at frequencies well into the MHz range. Between these resonant peaks the device has broadband characteristics and high frequency applications including medical ultrasound probes utilise this feature. Dielectric impedance analysis is a method that characterises the materials low field (typically although high field analysis may also be performed) dielectric and ferroelectric behaviour. For example, permittivity, loss tangent and PE loop analysis are readily measured. However, its acoustic properties are often those of most importance that are only realised under

conditions of high drive fields and so techniques have been developed to investigate these characteristics.

Since the acoustical performance of piezo-composites may be related to its displacive properties it is prudent to develop methods that record the surface displacement profile of actuating composites. Some early work carried out that characterised the d_h response as a function of temperature and frequency utilised a novel laser Doppler vibrometer to record the out-of-plane surface displacements of a 0-3 composite [11]. This work demonstrated that the technique was an effective method in determining the piezoelectric coefficients. In order to design improved composite transducers the need for accurate models that can be used to predict piezo response became apparent. Several attempts have been published that develop analytical models that predict the surface displacement of piezo rods in a polymer matrix [12 & refs within]. Assumptions that the poled piezo rod is isotropic were considered to be inaccurate since the charge coefficients parallel and perpendicular to a poled rod are not identical. To cope with this, Sottos [12] developed analytical methods that describe the transverse isotropy of the rods and includes an analysis of the presence of an interphase between fibre and matrix. In experimental studies Sottos [12] found that the addition of a harder and stiffer interphase significantly reduced the total rod displacement under the application of a static electrical field, agreeing with their theoretical predictions. The presence of a stiffer matrix further was observed to reduce the piezo rod total displacement.

Similar experimental studies involving the measurement of fibre/matrix displacement profiles have been used to characterise the effects of matrix and interphase on total displacement [7, 13-16]. Two separate types of displacement profile tests are typically conducted, static and dynamic. The static test involves the measurement of the out-of-plane displacement (via interferometers for example) of piezoelectric rods surrounded by matrix to investigate the effect of matrix drag or uplift and interphase interactions [13]. Alternatively, since the piezocomposite transducers are more often used at high frequencies for ultrasonic applications, their dynamic surface displacement characteristics are measured [11][12] [15][17][18]. Using dynamic observations, it is possible to extract more information regarding the effect of matrix/interphase compliance, frequency, modal analysis and phase analysis. The purpose of this study was to investigate the use of two methods of measuring the out-of-plane displacements of a range of 1-3 piezo-composites. The uplift of the matrix surrounding closely-spaced piezo-rods or piezo-fibres has been observed and the general reduction in matrix displacement in regions away from active material is discussed. The methods have been compared and ways in which the data may be visualised for greater understanding of the effect of composition, volume fraction, aspect ratio etc. have been explored.

2 EXPERIMENTAL METHODS

All samples were of 1-3 type configuration, shown schematically in figure 2. The 1-3 composites were purchased from Smart Material Corp. FL, USA, (www.smart-material.com) and one was manufactured in the laboratory:

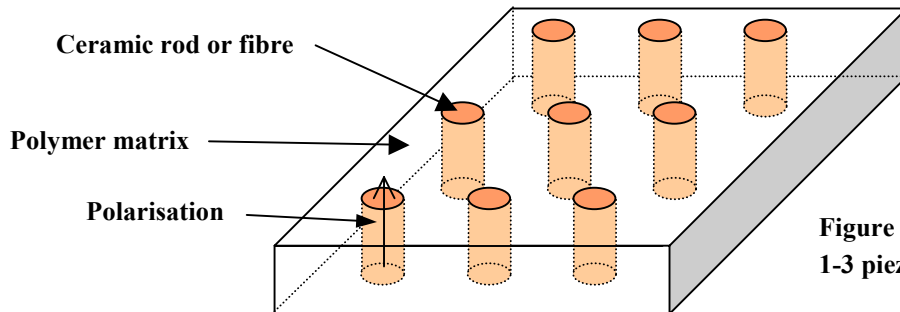


Figure 2: Schematic of 1-3 piezocomposite

1. B25A1-25104ACP, 1mm thick, 5A1 material, 250 μ m diameter fibres, Araldite 2020 CIBA GEIGY epoxy, poled and gold electroded, figure 3.

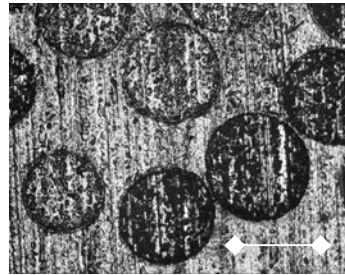


Figure 3: As-received sample. The sample surfaces were coated in gold. Bar – 250 μ m.

2. B15H1-0810ACP, Regular structure, PZT 5H1 material, 180 μ m thickness, pixel structure 88 μ m x 44 μ m, Araldite 2020 CIBA GEIGY epoxy, poled and gold electroded, figure 4.

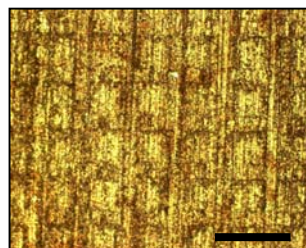
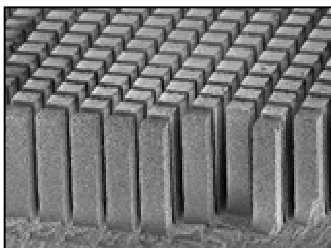


Figure 4: As-received sample. The sample surfaces were coated in gold. Bar – 200 μ m.

3. Laboratory, non-commercial sample, University of Bath, manufactured by Luke Nelson: i.d. 235 VSSP 55, 5mm thick, 235 μ m diameter fibres from Advanced Cerametrics, Struers Specifix 40 epoxy resin, figure 5 [19].

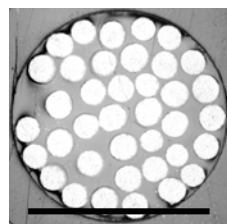


Figure 5: Polished cross sectional image of laboratory manufactured piezo-composite. Bar – 3mm.

The surface displacement of 1-3 composites has been measured using two techniques. The first is a static technique and is based on surface laser profilometry typically used to characterise the surface roughness of materials. The second is a dynamic test method that may be used to measure the surface displacement or velocity from near DC to several MHz. Here a Doppler laser vibrometer is used to measure absolute surface displacements or surface velocities. Both methods will now be explained in more detail.

2.1 SURFACE PROFILOMETER – STATIC OR DC TECHNIQUE

The surface profile of piezoelectric samples may be measured using a scanning profilometer. A UBM optical profilometer system (<http://www.ubmusa.com>) was used to measure the surface height changes that accompany a stepwise increment in DC voltage when applied to the piezocomposite sample. The CD ‘Autofocus’ depth-sensing head was used. The sample was positioned on the XY scanning stage using double-sided tape and electrodes attachment as shown in figure 6.

The samples top surface (held at zero volts) was connected to the electrode post using thin copper wire. The UBM system is a scanning system and 3-D maps of surface displacement or 2D contour maps could be imaged and saved. Careful control of the sensor head filtering and damping coefficients (software controlled) were made to enable a higher signal to noise ratio, and to reduce the effect of resonant ringing. An initial scan at zero applied volts was taken followed by successive ones at higher DC voltages to build up maps of surface displacement with field. Scan rates of 0.05mm/second were used to build up images of 200 x 200 data points. The scanned area was 1mm square for all images. The sensor set-up was set to ‘fast’ and to option ‘5’ or ‘1’, to minimise ringing.

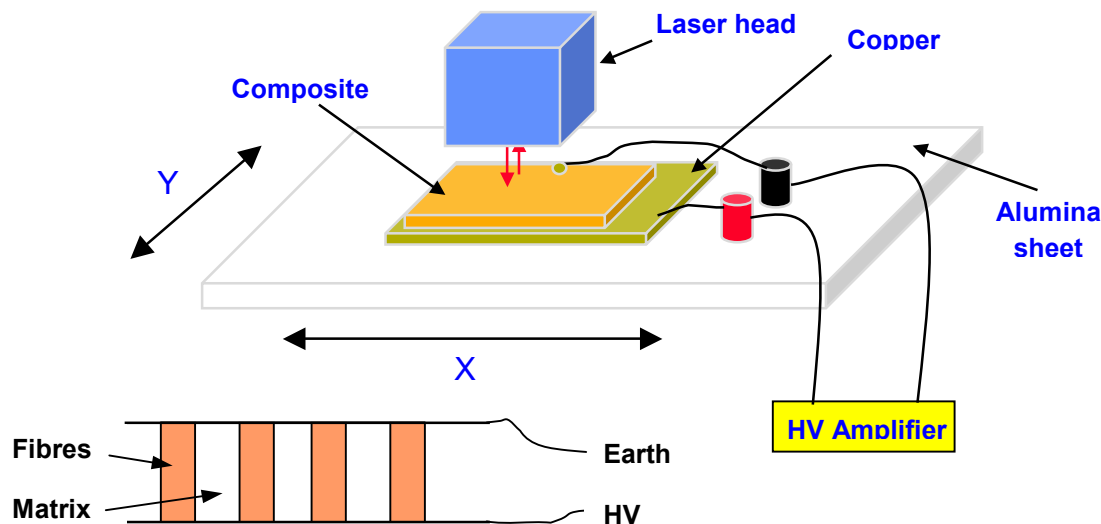


Figure 6: Schematic showing experimental set-up for UBM scanning profilometry. Note, the entire top and bottom surfaces were electroded.

The datasets were saved and later calibrated, imaged and analysed using software procedures written in IDL (© Research Systems, UK). Displacement differences were obtained by the subtraction of the high voltage image from the zero voltage image. To check that the difference images were simply not artefacts of slightly misaligned images (that would create an image depicting displaced fibres), the subtraction process was also carried out on two zero voltage images taken sequentially. The sample must be either electrically shorted or left for

some time between any measurements at high electrical field so that any stored charge is reduced to zero, or residual strains will be present. Voltages up to 900V DC were applied to the sample.

2.2 LASER DOPPLER VIBROMETRY – AC TECHNIQUE

The AC or dynamic characterisation of piezo-composites has been explored using various techniques, typically based on non-contact laser interferometric methods. In this study, the displacement was measured using a Polytec dual beam differential laser Doppler vibrometer (www.polytec.com). The measurement of displacement of a moving surface is complicated by the fact that, in piezoelectric materials, the displacement being measured is typically very small ($< 1\mu\text{m}$). Thus the measurement system must have sufficient sensitivity and resolution to be able to map out the surface displacement to approximately 10nm for these studies. Laser Doppler vibrometry (LDV) is a non-contact vibration measurement technique that utilises the Doppler effect. Here, reflected laser light from a moving surface experiences a shift in frequency compared to its original beam (or reference beam) according to the Doppler shift equation, equation 1.

$$\Delta\nu = 2v \cos \theta / \lambda \quad (1)$$

where $\Delta\nu$ is the shift in frequency of the laser light (or in the case of the Polytec system, this is equal to the change in the RF modulated frequency (40MHz)), v is the velocity of the reflecting surface, and θ is the angle between the transmitted and reflected beam. λ is the wavelength of the laser.

The Doppler frequency shift is thus proportional to the surface velocity and the displacement may be calculated as the integral of the velocity since $v = d\phi/dt$ where ϕ is the displacement. [11]. The Polytec system does not rely on this integration to decode displacement, rather it has separate displacement decoding electronics that utilises the phase information of the Doppler signal providing a digital fringe counting method.

Laser vibrometers are typically two-beam interferometric devices that detect the phase difference between an internal reference and the measurement beam. The measurement beam is focused on the target and scattered back to the interferometer. The heterodyne principle used in Polytec vibrometers generates an FM carrier to provide the directional information. In the system employed at NPL, two beams are made externally available, in the form of fibre optics terminated with focusing optics. One beam is the reference and must be positioned on a non-moving surface sited as close as possible to the sample. The other beam is the measurement beam that is reflected off the moving surface of the sample. The difference between the reference and measurement beam lengths must be kept as close as possible to 0mm or multiples of the coherency length of the lasers (in this case about 70mm).

More information about the operation and design of Laser Doppler Vibrometers may be found in [11] and on the Polytec web site.

The technique employed utilised the Polytec differential LDV and a lock-in amplifier to increase signal-to-noise for our displacement measurements. A sinusoidal waveform was generated using a Thurlby Thandar Frequency generator (<http://www.tti-test.com/>) and applied to the input of a high voltage amplifier. The high voltage output of the variable gain amplifier (B&K) was connected to the piezocomposite using the same arrangement described above for the UBM set-up. A small piece of special reflective tape was applied to the surrounding alumina substrate holding the sample that acted as the reference reflector for the LDV. The laser vibrometer reference beam was aligned with this reflective tape and the measurement beam aligned with the sample surface. The sample surface was cleaned using an alcohol to remove any traces of dirt or dust. The displacement output from the OFV-3001 module (LDV) was connected through a divide-by-10 attenuator to the signal input of a digital Lock-in amplifier (Stanford Research SR844 www.srsys.com). The reference input to the SR844 originated from the drive signal to the sample that was taken from the monitor output from the high voltage amplifier. A divide-by-50 attenuator was required in this instance to make certain that the lock-in was never overloaded. The R and θ outputs (amplitude and phase) were saved to disc using specially developed software written by NPL using LabView (©National Instruments – www.ni.com). The whole system was arranged as in figure 7.

This set-up enabled the absolute measurement of displacement by the recording of the lock-in R signal output. In the system used, the lock-in was operated using its high input impedance buffers (*ref in* and *signal input*) that provided a further gain of x2. This gain factor was taken into account when calculating the actual displacement in micro-metres (see below for explicit description). Throughout most of the experiments the LDV was set at its highest *sensitivity* of

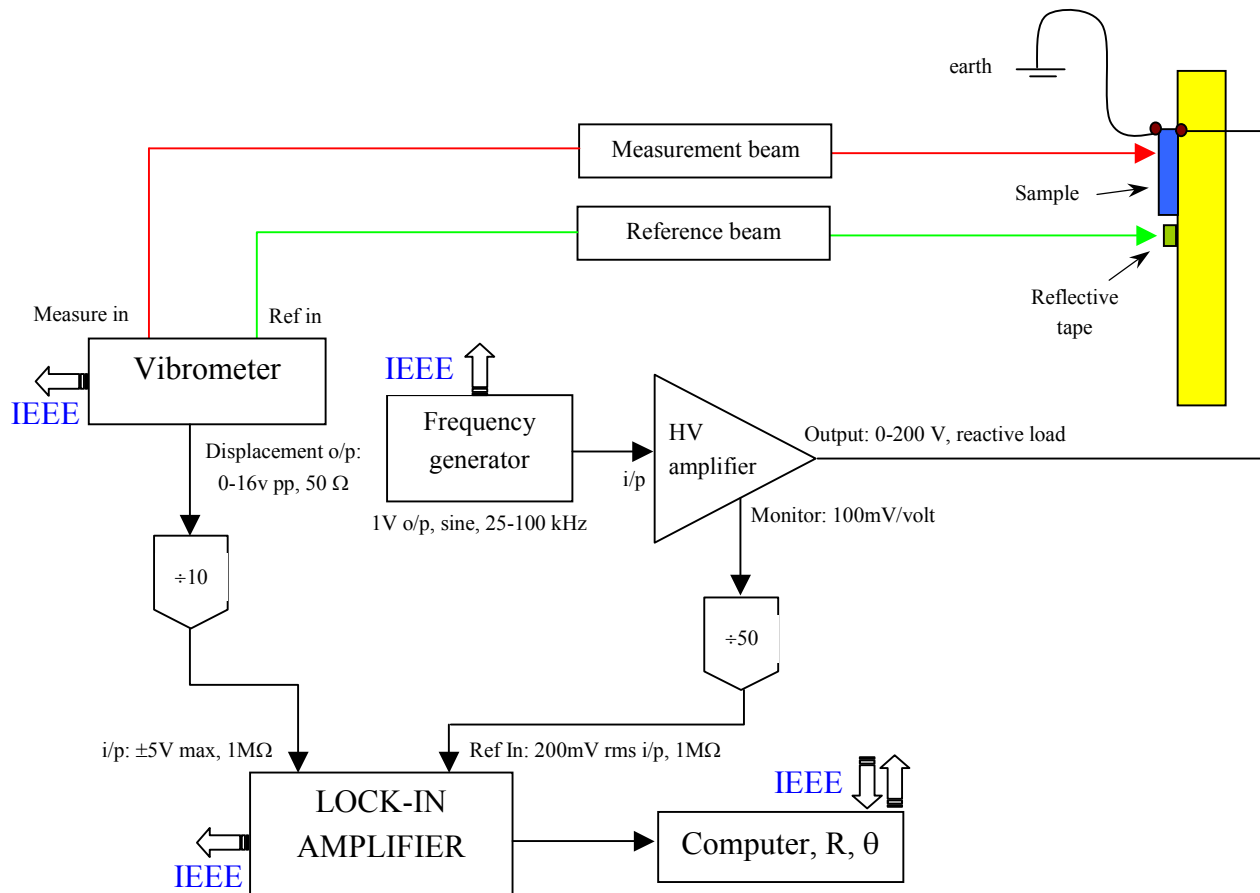


Figure 7: Schematic showing set-up for LDV measurements.

0.5 $\mu\text{m}/\text{V}$ output, with its proprietary *tracking filter* also switched in and set to *slow*. This reduced the chance of the unit losing its velocity-tracking signal when operated at frequencies above 20 kHz. (For more information on the operation of the Polytec LDV please refer to the web site above and its Instruction Manual).

The measurement procedure included a calibration run of the high voltage amplifier's *monitor* output and the SR844 lock-in amplifier. Using a calibrated oscilloscope the voltage waveforms of *signal input* (from function generator), *monitor output* and *high voltage output* were compared and a calibration curve drawn. The monitor output was scaled according to the manufacturer as 0.1V/V and was calibrated to within 2% of this value. The lock-in amplifier was augmented with the attenuators needed to reduce the otherwise harmful high voltages to acceptable levels. The calibration thus included these systems connected as shown in figure 7. Application of a 1000mV sinusoid p/p at the signal input resulted in an output of 28mV. The theoretical calibration factor for this system should have been $1000 \div 10 \div 2 \sqrt{2} = 35\text{mV}$. The error arises from the actual attenuation value of the $\div 10$ attenuator, being closer to $\div 12$. The calibration of the reference signal is less important in that it only provides the reference lock-in needed to lock the signal input to increase signal-to-noise. The final gain factor needed to take the R output from the lock-in and translate into a real displacement in μm was: gain factor = $0.5 / (2 \times 2 \times 0.028)$.

Various experiments were carried out including:

- Optimisation of the system (refer to the instruction manuals for Polytec Vibrometer, and SR Lock in amplifier) and equipment set-up.
- X-Y scans of surface displacement of three piezo-composites, driven at various frequencies and field levels. The images thus obtained, represented displacement via intensity of grey scale from black to white, or in some cases where colour coding has been used, the levels are indicated separately.
- Contour maps were generated to depict the displacement profile.
- Line scans extracted from the X-Y surface scans were compared to simple analytical solutions of the displacement of piezoelectric fibres embedded within polymer matrices.
- Animated sequences of displacement profiles with frequency and applied voltage have been recorded and displayed on our web site and included in this document as a mpeg file. (www.npl.co.uk/npl/cmmf/functional/piezocomposite.html)

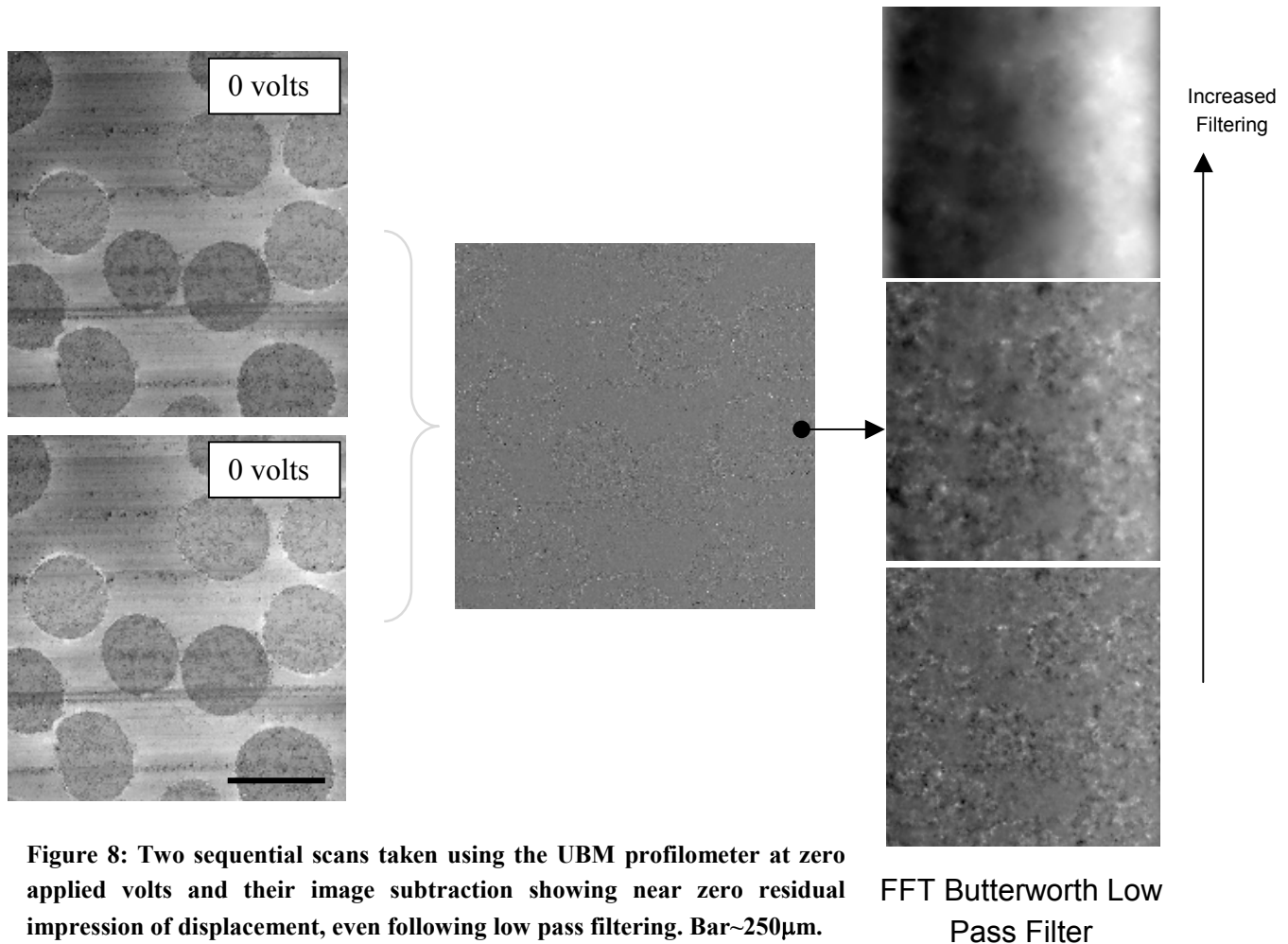
3 EXPERIMENTAL RESULTS AND DISCUSSION

3.1 STATIC SYSTEM – UBM SURFACE PROFILOMETER

Piezocomposite Sample B25A1-25104ACP – a random array of 5H type piezoelectric fibres in an Araldite 2020 epoxy matrix was investigated using this first approach. The scans were carried out at a scan rate of 0.05mm/sec and an area of 200 x 200 points delineated a 0.5 mm square region within the centre of the composite plate. The sample electrodes (covering the entire top and underside surfaces of the composite) were shorted together and two scans were carried out at zero applied volts. The scans in figure 8 show these two sequential scans.

The residual image (central image in figure 8) has been reproduced using contrast enhancement techniques (histogram equalisation) that spread the almost zero intensity (black)

image into a grey scale one with the result of a 50% grey-level covering the majority of its area. It is clear that after software subtraction of one image from another, very little impression of the fibres is evident. It is important to remember that the initial image identifying the arrangement of piezoelectric fibres is a surface profile of height and not displacement. It is thus evident that the piezoelectric fibres are extended beyond their surrounding matrix. Once the images are subtracted then we should expect to see a constant and uniform surface roughness indicating zero net displacement changes during the first and second run. This is what is observed and lends credibility to the technique.



Displacement maps were then carried out on the same sample, actuated with voltages from 500-900 volts DC. The scans were performed in an identical manner to that already described, the scans saved and images subtracted from identical zero volt scans. In this way, evidence of net displacement may be imaged, identifying the extent to which the matrix deforms in the vicinity of the fibre. The images in figure 9 shows a scan at zero volts and a scan at 800 volts. At this stage the grey levels (always histogram equalised for viewing) indicate height and not displacement. Only when we subtract one image from another do we obtain displacement data.

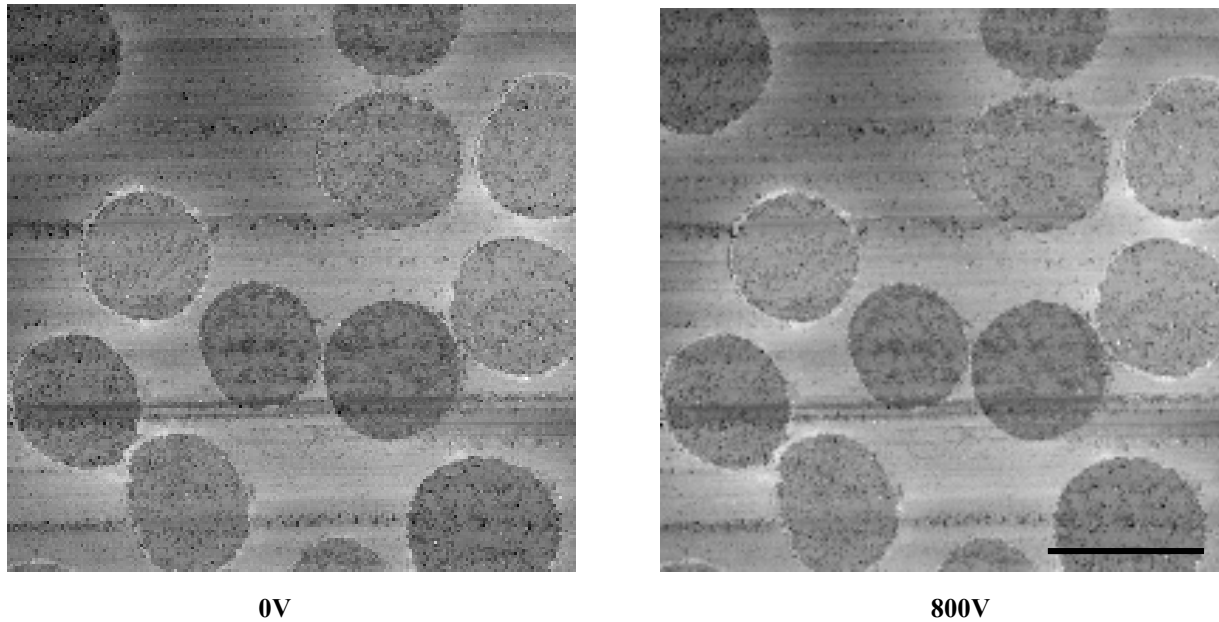


Figure 9: Images showing height maps of scanned surface at zero volts and 800 volts. Bar ~ 250 μ m.

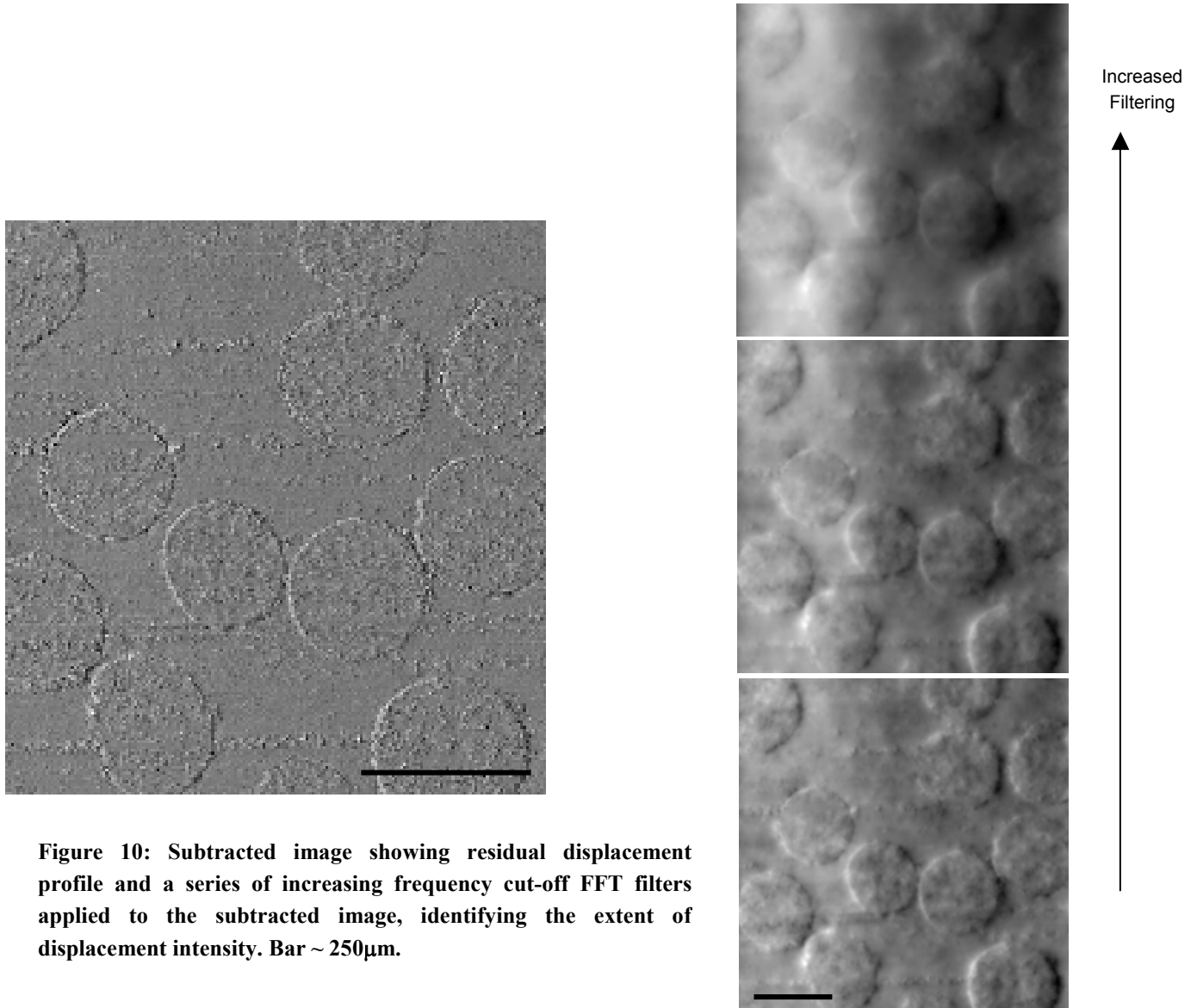
The images in figure 10, shows the raw subtracted image and a series of FFT (Fast Fourier Transform algorithm) filtered images of increasing cut-off frequency (based on a standard Low Pass Butterworth filter) identifying regions of matrix that uplift following the displacement of the fibres. These regions of matrix being ‘dragged’ by the piezo fibres has been noted elsewhere [14], where it was observed that the two displacements were often out of phase as a function of time, something that is not measurable using this static technique. In this cited work, the maximum displacement of the fibres was about 10% larger than the maximum displacement measured from the matrix. The effect of the polymer matrix and more importantly the interlayer region between the fibre and matrix on the displacement profiles has been demonstrated by various authors [15, 13, 12] and modelled using linear analytical methods. Such models have accurately predicted the profile of displacement as the measuring probe scans across the top of a fibre into surrounding matrix. Depending on matrix stiffness, and interlayer properties the profile may be observed to change quite radically. Indeed, experimental work has shown that the effective d_{33} , and d_{31} , decreases with increasing interlayer compliance [7] although the value of d_h actually increased with increasing interlayer compliance because change in $-2d_{31}$ is larger than the change in d_{33} .

The qualitative changes in displacement from figure 10 may be useful to designers of piezo-composites in that, modifications to matrix chemistry would result in changes to the displacement profiles and hence transducer performance. An example taken from these measurements may be used to illustrate this concept. Figure 11 shows one of the displacement subtraction images that has been run through a FFT filter removing all high frequency contributions to the image. In this way, instead of surface roughness being dominant we are observing more of the form of the surface – e.g. the general trends across a larger area.

The ‘blurred’ edges and regions between closely adjacent fibres showing up as a lighter grey level than the regions far from any fibres indicates the effect of matrix uplift. In all these

images, the lighter the contrast, the more the displacement. These issues will be dealt with quantitatively in more detail in a future paper.

Static tests are clearly useful methods to characterise the surface displacement profile of piezo-composites. In order to understand how the composites perform under dynamic tests the Laser Doppler Vibrometry method was utilised.



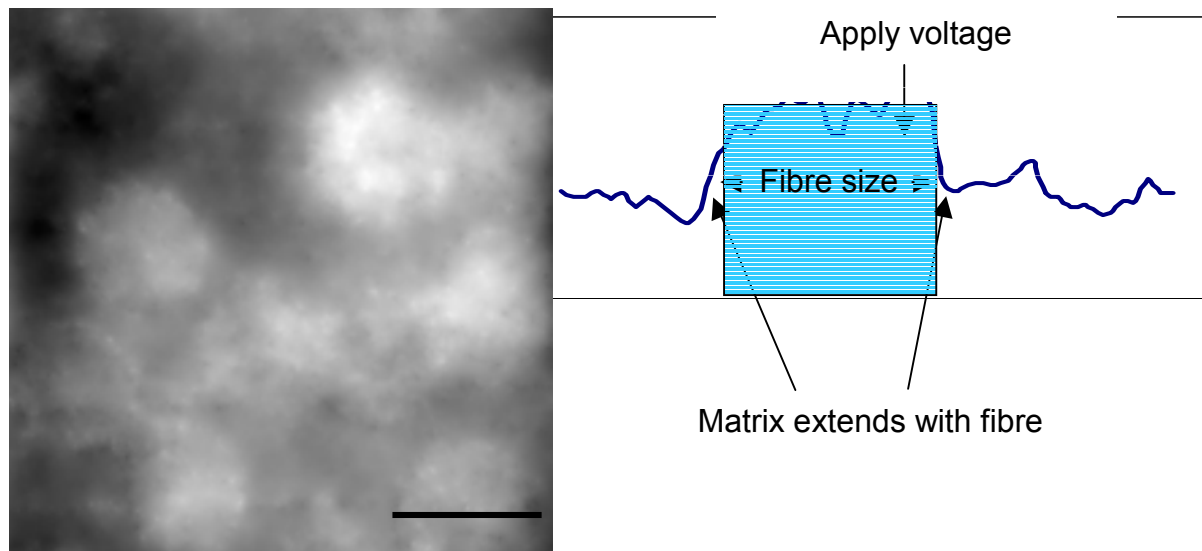


Figure 11: FFT filtered displacement map of sample excited by 800 volts DC, and data extracted from surface profile showing effect of uplift on composite displacement profile. Bar ~ 250 μ m.

3.2 DYNAMIC SYSTEM – DOPPLER LASER VIBROMETER

Applying an ac voltage across the poled sample using the high voltage amplifier actuated the piezo-composites. The lock-in used as a reference the monitor output of the high voltage amplifier and as input the displacement output from the LDV. The R-value recorded from the lock-in was equal to the actual displacement x gain factor, described in the experimental method.

Three types of measurement were taken, on three different samples. The first measurements recorded the surface displacement profile of the sample at different frequencies ranging from 25kHz (minimum for the SR844 lock-in amplifier) to 45-60kHz. Both displacement amplitude and phase were recorded. The phase information is relative to the ref-input to the lock-in, which was the monitor output voltage. Thus, the phase signal may yield information on the lag or lead (phase difference) between fibre extension/contraction and matrix displacement, as a function of frequency. Previous work investigating the phase difference as a function of time from onset of applied voltage to an arbitrary value of time has shown that depending on the type of matrix used, the uplift was observed to occur behind fibre displacement or following fibre displacement [14]. In this series of measurements, this type of analysis was not performed. The second series of measurements were taken at one frequency with different levels of FFT frequency domain filtering in order to accentuate the effect of matrix up-lift. The third type of measurement was taken on one sample at different voltage levels and a sequence of images were assembled to form an animated gif file, showing the changes in displacement and effects of matrix uplift with electrical field.

The image in figure 12 shows the piezocomposite sample id B25A1-25104ACP, surface displacement profile in a 3D contour orientation. The sample was excited using a sinusoidal voltage of 175V. The fibre outlines are clearly evident as is the extensive matrix up-lift surrounding the closely spaced fibres, with much less of a matrix displacement in regions of less dense fibre occupancy. The levels of displacement, z-axis, have been corrected for the various gain values, described in section 3.2, indicating a d_{33} of ~ 285pm/V. From the

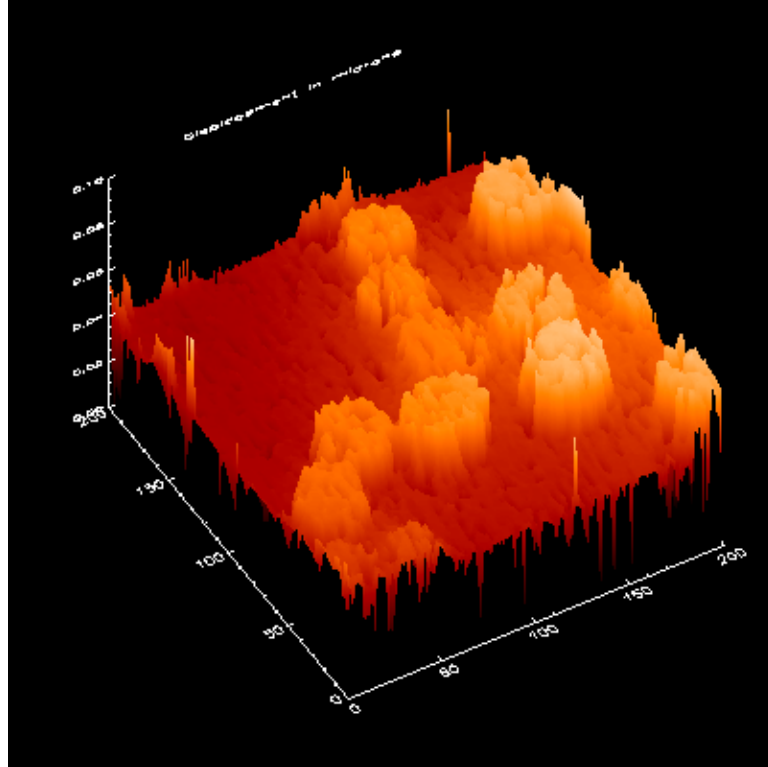


Figure 12: Surface displacement contour map of sample B25A1-25104ACP.

theoretical work of Skinner et al. [20], the effective d_{33} , for a composite of volume fraction 50%, and a polymer compliance of $\sim 2\text{GPa}$, yields $d_{33}^{\text{eff}} \sim 0.9 d_{33}$. d_{33} for a typical 5A class material is $\sim 374\text{pm/V}$ [21]. The reduced value would thus be $\sim 337\text{pm/V}$, still in excess of the value measured. It is unlikely that the d_{33} value for the piezofibres can be represented by the bulk value, due to differences in poling history, microstructure (porosity and grain size) and compositional variation.

The second set of experiments conducted on this sample was a frequency scan from 25kHz to 45kHz in steps of 5 kHz. Both amplitude and phase are displayed in the images in figure 13, 14, & 15. The effect of frequency on the phase signal (between displacement and applied field) indicates the different dynamic properties between the fibres and matrix. At certain frequencies the surrounding matrix is clearly significantly more out of phase to the fibres than at other frequencies, figure 15. It would be interesting to be able to model this effect, although this was beyond the scope of this task, but may be included in a future publication. The displacement behaviour at 25kHz clearly shows the difference between regions that are highly occupied with fibres and the more sparse areas, mostly devoid of fibres, figure 13 and figure 14. The highly populated regions exhibit cooperative uplift of matrix with fibres whilst the opposite is true for less densely populated regions of matrix. The type of information that may be gleaned from studies such as this includes the effect of a change in distribution of fibres on the effective d_{33} of the composite, and its acoustic performance. Large patches of matrix unoccupied with fibres are mainly inactive which may lead to acoustic ‘holes’ or non-uniform acoustic fields propagating in the length extensional mode of normal operation.

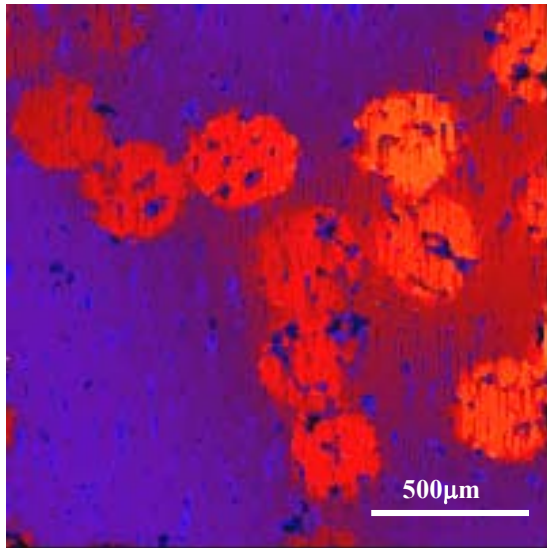


Figure 13: Displacement map at 25kHz

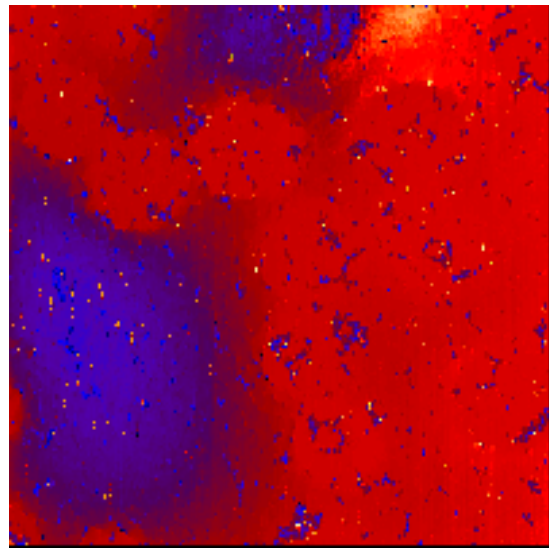


Figure 14: Phase field map at 45kHz

The intensity differences across the series are arbitrary changes in use of colour mapping, and in these cases do not represent actual displacement values, except that the regions in red are of a higher displacement than the areas coloured purple/blue. In these images the important observations include the changes in matrix performance with frequency and fibre interaction with the surrounding polymer.

Sample id. B25A1-25104ACP
 200x200 scan. Step size 25.
 F=25, 30, 35, 40, 45, kHz

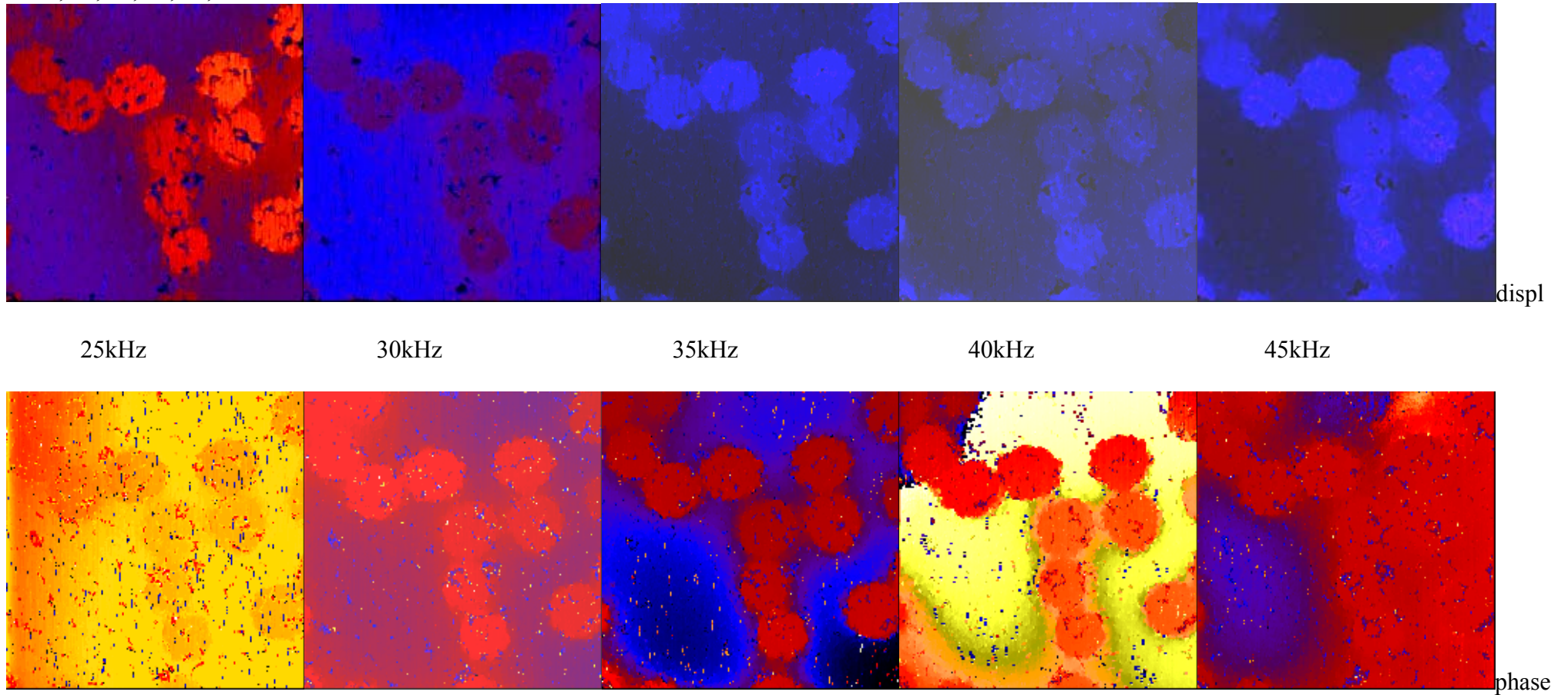


Figure 15: Frequency scan for sample B25A1-25104ACP (Random array). Bar ~ 500 μ m.

The final experiment carried out on this sample, B25A1-25104ACP, was a higher frequency large area scan of displacement. The sample impedance was measured using an HP4294A impedance analyser, where a resonant peak at $\sim 61.6\text{kHz}$ was observed. The sample was then placed within the experimental set-up of figure 7 and a displacement scan was recorded using the LDV, figure 16. In these images, the edge of the sample can be clearly seen in the displacement scan. An interesting pattern emerges that may be characteristic of a resonant mode operating within this sample. Again dynamic FEA would help identify which mode may be operating, - this will be carried out in a future paper. The effect of the FFT is clearly demonstrated in the same figure with the images presented in reverse order of filtering effect. Sometimes the use of FFT filtering can accentuate the underlying pattern of displacement or phase map reducing the image artefacts such as speckle, noise, and other higher frequency contributions. This depends on optimising the filter parameters such as cut-off length and power spectrum.

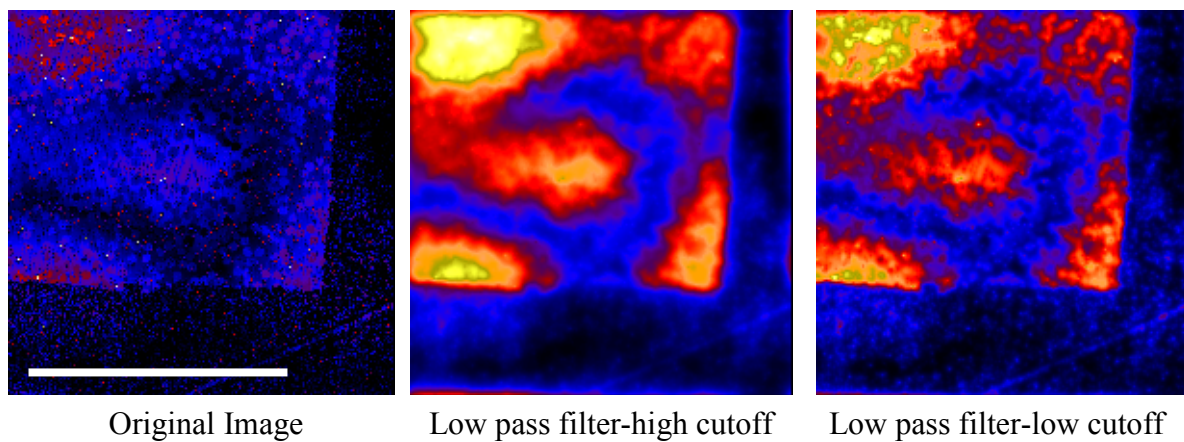


Figure 16: ‘Resonant’ Frequency scan for sample B25A1-25104ACP (Random array). Bar ~ 10 mm.

The regularly spaced sample, id. B15H1-0810ACP, was next characterised using the LDV system, at 25kHz driving frequency. The sample exhibited a uniform and homogenous displacement map and similarly uniform phase field, figure 17, 18. The presence of some matrix rich regions – such as top left, and bottom middle, figure 17 – is identified clearly as areas of lower displacement, and also as areas of different phase contrast. The effect of porosity has not been discussed, and although the areas arrowed in figure 17 may indeed be pores, the displacement maps should penetrate these imperfections to some degree, since the images represent displacement. However, the differences in the quality of reflected light from a ‘hole’ that has different surface roughness properties compared to the polished surface may affect the way in which displacement (or velocity) is measured using the Polytec LDV.

The random array sample was 1mm thick, whereas the regular array structure only $180\mu\text{m}$ thick. It is well understood that one of the more important factors influencing the performance of a 1-3 piezocomposite is the aspect ratio (AR) of the active component. The AR for the random array is approximately 1:4 (length of piezo-fibre to cross sectional dimension - diameter) and for the regular array approximately 1:2.3 which is about half the former value. The effective d_{33} has been shown to linearly depend on AR [22] with a decrease in d_{33} following an increase in AR (reducing the fibre length). This can be attributed to the non-uniform stress distribution that develops within the fibre and matrix when a stress is applied across the composite faces. Although in this work we have not aimed to quantify this effect, it is worth noting that FE analysis that calculates average strain from an applied

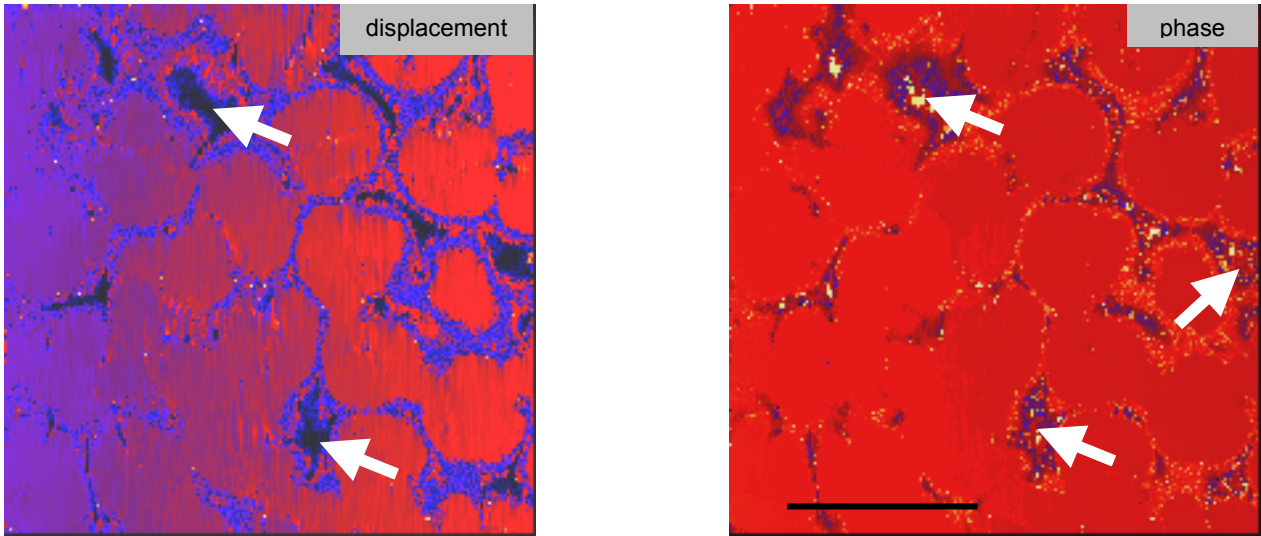


Figure 17: Sample B15H1-0810ACP (Regular array) showing matrix rich regions, arrowed. Bar ~ 150 μ m.

voltage may not reveal this AR effect since the electrical fields are less distorted than their mechanical analogues [22]. The original square array imaged in figure 4 is less clearly evident in these displacement maps. The piezoelectric elements in fact appear more round than square in these out-of-plane displacement profiles. The reasons are unclear, and further lower frequency measurements are required to explain this phenomenon.

200x200 scan. Step size 6.

F=25kHz

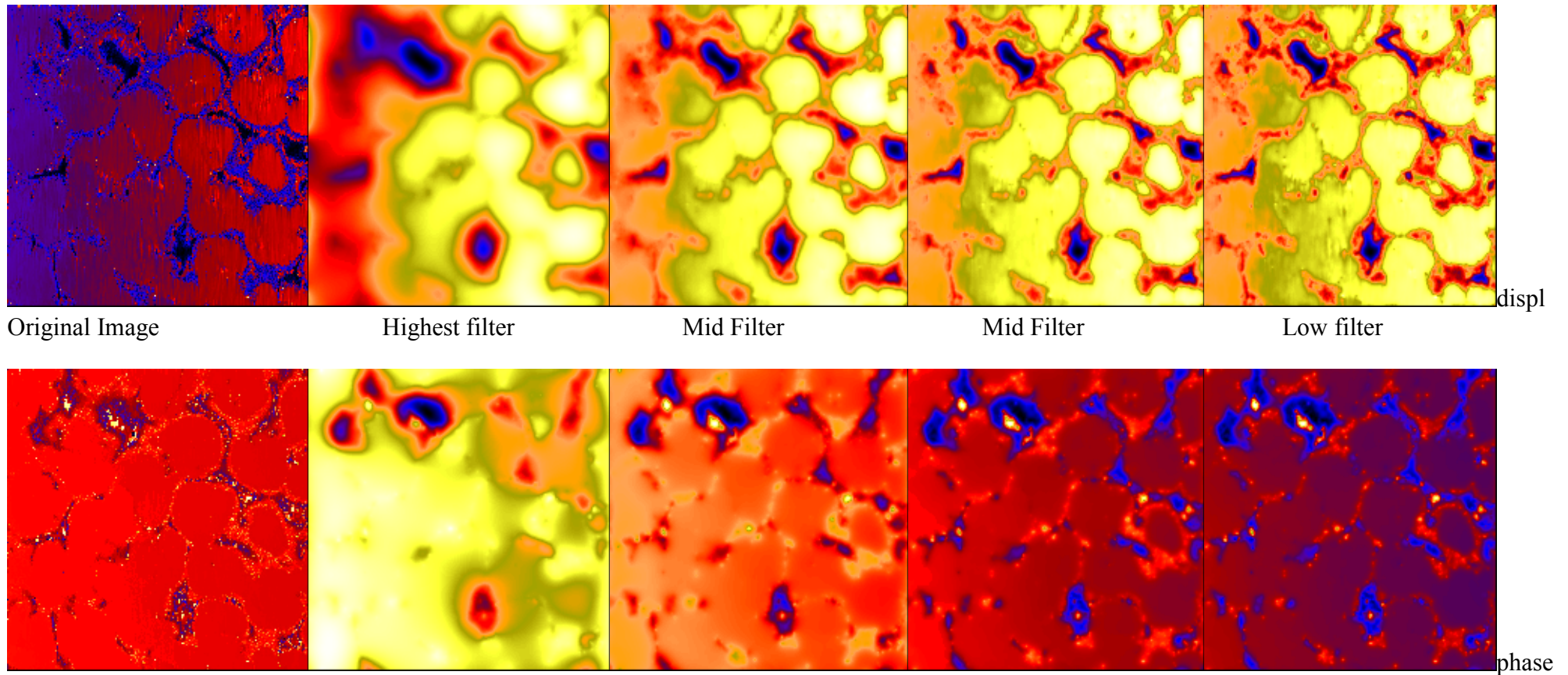


Figure 18: Single frequency scan for sample B15H1-0810ACP (Regular array). Bar ~ 150 μ m.

FFT-Fast Fourier Transform with Butterworth Low Pass Filtering from low to high filter cut-off lengths. 'displ'-displacement.

The final series of experiments was carried out on the laboratory piezocomposite, id. 235 VSSP 55. The samples were longer than the other plates and $\sim 3\text{mm}$ diameter. A frequency scan was performed and variations in displacement and phase can be observed in figure 19.

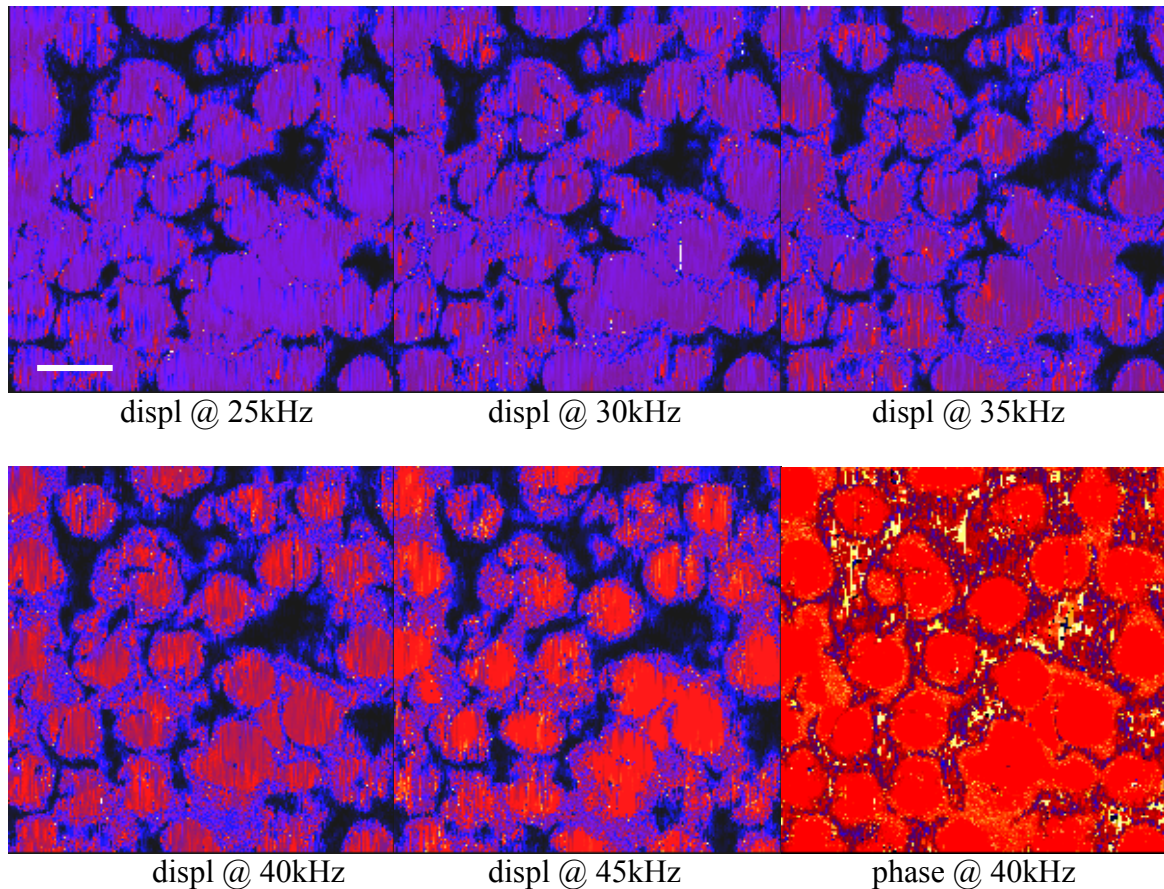


Figure 19: Frequency scan on piezocomposite sample 235 VSSP 55. Bar $\sim 500\mu\text{m}$. Qualitatively, red indicates high displacement and blue low displacement.

The effect of frequency on the displacement and phase characteristics is less clear in these images. The absolute intensity of the signal increases, as the frequency is increased, especially evident within the fibres, and there is more evidence of matrix uplift in this sample than in the much thinner commercial samples. The matrix appears to be affected by frequency such that at lower frequencies the matrix and fibres are acting as one homogenous material but at higher frequencies, there is evidence that the fibres are moving more independently of the matrix (there is a larger difference between their two displacements). This may be expected since the matrix would experience an increasing shear stress as the fibres attempt to drag the matrix with an increasing frequency of operation. The situation is highly non-linear since the viscoelastic properties of any polymer are frequency and temperature dependent. Additionally, the effect of time on the stress state within the polymer will also affect the piezocomposite performance since clamping of the piezo fibres by the polymer is time dependent. This is called stress relaxation of the polymer during which time the long-term mechanical properties (modulus, Poisson ratio etc.) are all strongly affected by its temperature/time/aging history. It is beyond the scope of this report to describe all these effects, but it is essential to understand them in order to be able to model the matrix behaviour in the presence of an active piezoelectric phase. A particularly relevant issue is that polymers exhibit a number of different relaxation times associated with the types of bonds

that are involved in its dynamic behaviour. For example, FTIR experiments are used to study the relaxation times (or resonance's) of the various molecular bonds that characterise polymer materials, with the finding that the mechanical and thermophysical properties and their associated losses (or damping) change with frequency. These experiments characterise the high frequency part of the polymer spectrum of relaxation times. For the low frequencies, a combination of mechanical and thermal experiments is usually chosen [23]. In terms of these measurements, it is not therefore unexpected that the phase (or damped motion) of the polymer matrix is not perfectly aligned to the piezoelectric fibres phase, but rather it changes according to drive frequency, drive field, aspect ratio etc. The situation is very complex although the various models described earlier incorporate the linear (and some the non-linear) properties of the polymer in describing the static displacement of the composite, and the dynamic response following a gradual increase in voltage. Further work will be carried out in this area at NPL, where the non-linear viscoelastic response will be coupled to the piezoelectric response in order to characterise the dynamic response of the 1-3 composite. Non-linear FEA will also be evaluated using new code developed during this DTI project (CPM8.1) by PACSYS.

4 CONCLUSIONS

Two methods for measuring the out-of-plane displacements of a range of 1-3 piezo-composites have been investigated. The first used a surface profilometer to scan the surface profile of 1-3 piezo-composites under static DC conditions. The second used a laser Doppler vibrometer to record the dynamic surface displacement profile of the composites at various frequencies and electrical actuation drive level. An uplift of the matrix surrounding closely-spaced piezo-rods or piezo-fibres has been observed and the general reduction in matrix displacement in regions away from active material is discussed. The methods have application to the study, design and improvement of current and research piezo-composites since their acoustic performance may be easily related to their displacement properties. The techniques may also be used to validate some of the newer models being developed that attempt to predict the surface displacement profile of active material embedded within a surrounding polymer

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