VISUALISATION OF THE SURFACE VIBRATION USING A PVDF FILM ARRAY

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Abstract

The ability to visualise the vibration of a structural surface is a big advantage when analysing the modal characteristics of the structure. This can be done using many accelerometers but can be a laborious, time consuming process. In addition, for small structures the accumulative effects of accelerometer mass can soon become a problem and adversely affect the measured natural frequencies. An alternative is to use a scanning laser doppler vibrometer (SLDV) where the surface can be scanned to passively obtain the surface velocity. These systems are very useful but can be expensive and difficult to use in confined spaces or within fluids. This paper investigates using Polyvinylidene fluoride (PVDF) polymer film as an alternative method for visualizing the surface vibration. PVDF film has been widely investigated as a sensor and transducer material due to its high piezo-, pyro- and ferro-electric properties. In can be easily fabricated into thin sheets (~ few μm) and as a result it is ideal for making small, very light piezoelectric sensors. An array of seventeen PVDF sensors was constructed and attached to a thinly clamped steel disk. The output of the array was recorded for the first six resonant frequencies of the disk and compared to simultaneous results obtained using a SLDV.

1. Introduction

The main objective of this work is to investigate the feasibility of using a PVDF array to identify various modal frequencies for complex objects when submerged in water. For such scenarios the use of an SLDV or conventional modal analysis using accelerometers becomes impractical.

Several papers have reported on the use of PVDF for vibrational and modal analysis. The majority focus on looking at the modal frequencies of a simple cantilever [2-5] and compare experimental results with theory. Chen et al [6] also investigates the modal frequencies of a cantilever but also extends the investigation to a simply supported plate. This paper reports on using an array of PVDF sensors to visualise the modal shapes of a rigidly clamped circular plate. The plate was vibrated at frequencies up to 1000 Hz and a PVDF array used to measure the modal shape at each of the modal frequencies. The results are compared to those obtained using a scanning laser doppler velecometer (SLDV) measured simultaneously.

Polyvinylidene Fluoride (PVDF) is a semi-crystalline polymer that can exist in a number of crystalline states. One of these states is ferroelectric and is responsible for PVDF’s piezoelectric property. It can be fabricated into large sheets with thicknesses ranging from 5 μm to 2 mm. It is cheap, compliant and easy to handle and it has a density and acoustic impedance that is very low compared to its ceramic counterparts. These properties make PVDF a very attractive candidate for use as a vibration sensor for modal analysis especially where sensor weight and structure interaction are important factors. A comparison of some of these physical parameters compared to some conventional ceramic piezoelectric material is shown in table 1.

Table 1. Comparison of some of the physical properties of the PVDF film, PZT and $BaTiO_3$

	PVDF, DT-052K/L	PZT	$BaTiO_3$
Dimensions	L= 30 mm, W=12mm, T= 52 μm		
Capacitance [pF @ 1kHz]	650		
d_{31} [(pC/m^2)/(N/m^2)]	23	-80 to -270	78
d_{33} [(pC/m^2)/(N/m^2)]	-33	200-600	200-400
g_{31} [(V/m)/(N/m^2)]	216 x 10^{-3}	10x10^{-3}	5x10^{-3}
g_{33} [(V/m)/(N/m^2)]	-330 x 10^{-3}	-10x10^{-3}	5x10^{-3}
Youngs Modulus Y [10^{10}N/m^{2}]	0.3	11-12	6-9
Speed of sound [m/s]	v_{31}=1500, v_{33}=2200	3100	4700
Rel. Permittivity ε	12	1200	1700
Density ρ [kg/m^3]	1780	7500	5700
Acoustic Impedance Z [kg/(m^{2}s)]	2.7	30	30

As with other piezoelectric material, PVDF is highly anisotropic with its mechanical and electric properties having different responses in different directions. This anisotropy arises during the manufacture process where the film is initially subjected to a uniaxial loading while being heated to temperatures in the range 60–80^{o}C. Electrodes are then deposited on both sides of the PVDF and the film thermally polarised at 100^{o}C in an electric field of 500 to 800 kV. The film is then cooled in the electric field to “freeze” the polarisation. Due to this anisotropy it is necessary to identify the axes of the PVDF film with the numerals shown in Figure 1. L and W correspond to the length and width of the conductive electrodes across which the voltage is measured. t is the thickness of the PVDF film and g_{3n} corresponds to piezoelectric voltage coefficient in the three directions n=1,2 and 3

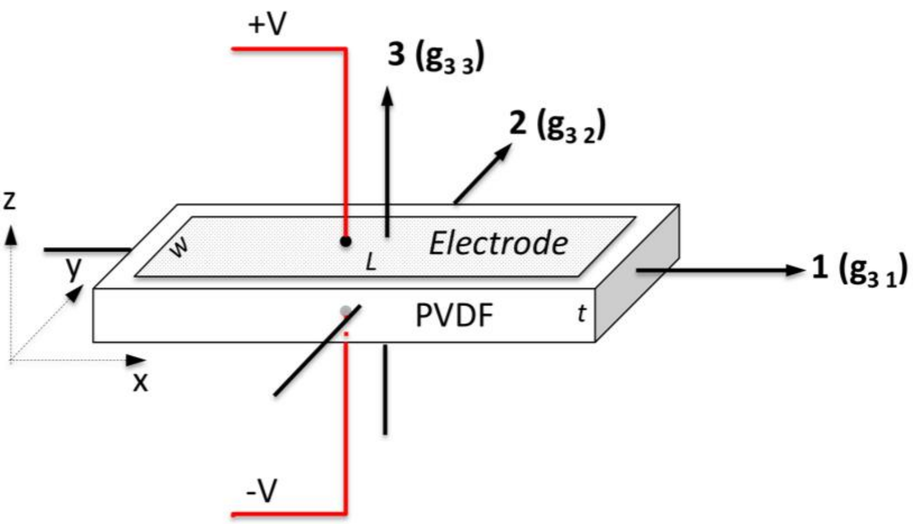

Figure 1. Axis Nomenclature for piezoelectric parameters

2. Sensor Fabrication and Characterisation

Sensors for this work were constructed from 52 μm thick PVDF film purchased from Measurement Specialties [1] (DT1-052 K/L). The original films consist of a 12 mm by 30 mm active area of PVDF with silver electrodes screen printed on both sides. They come supplied with attached leads. In order to reduce electromagnetic noise these films were folded in half and glued such that their outer electrode acted as a conductive shield around the PVDF film. In doing so this resulted in PVDF sensor films with an active area of 12 mm by 15 mm and an overall PVDF thickness of 104 μm. Relevant properties of the PVDF film are shown in Table 1.

The wires provided with the DT1 films were replaced with light gauge coaxial cable and SMB connectors attached to the end. The sensors were connected to a 4395A Agilent spectrum analyser and the noise levels of the sensors measured from 1 Hz to 2000 Hz with a frequency resolution of 1 Hz. The modifications made to the films resulted in a significant reduction in noise compared to the original sensor. A comparison is shown in Figure 1. The blue spectrum corresponds to the original DT1 film and the black the modified folded sensor with coaxial cable. As can be seen a reduction of ~20 dBV has been achieved over the entire frequency range from $0 < f < 2000$ Hz. The peaks observed in both spectra are from 50 Hz noise and its harmonics.

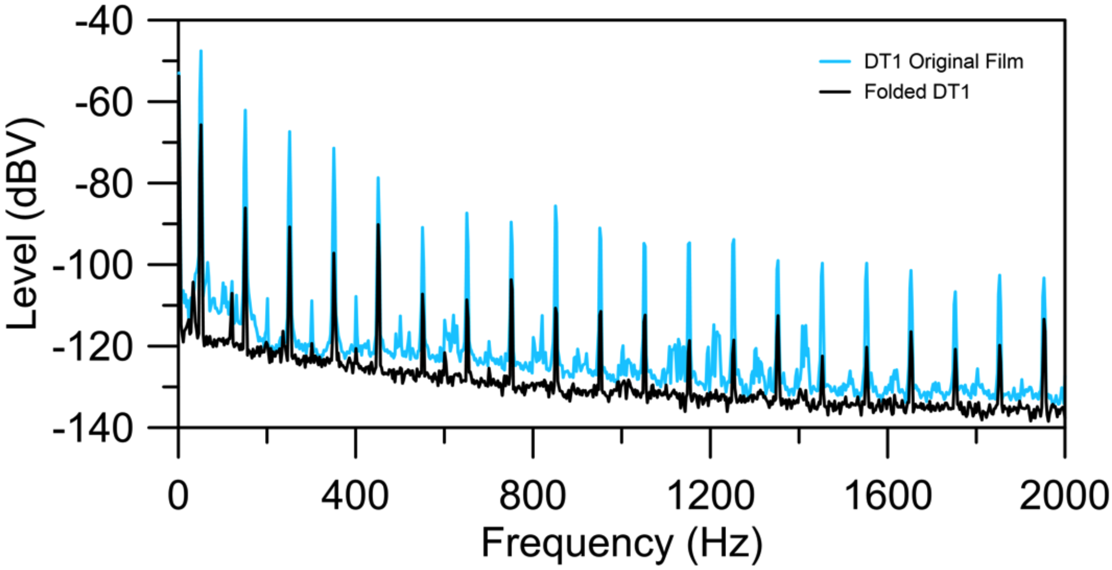

Figure 1. Noise spectrum comparison for the original DT1 film as supplied compared to the folded DT1 film with coaxial cable and SMT connector

The same procedure described above was used to construct seventeen folded sensors. In order to check consistency in their sensitivities an impact hammer was used to provide a force impact perpendicular to the face of the film (parallel to the 33 direction). In this case the initial charge density D_{A_F} (pC/m^2) generated on the PVDF film is given by

$$D_{A_F} = d_{33}\frac{F}{A_F} \tag{1}$$

where d_{33} is the piezoelectric coefficient in the 33 direction, F is the applied force and A_F is the area of the applied force. The charge Q developed is therefore given by

$$Q = d_{33}\frac{F}{A_F}A_F = d_{33}F \tag{2}$$

This charge instantly flows over the entire electrode area A_E. When using a charge amplifier to measure the output of a PVDF film (as opposed to a voltage amplifier) it measures the charge Q given by equation (2). As can be seen this charge is independent of the applied force area. In order to calibrate the PVDF films in the 33 direction each of the films were connected to a B&K type 2635 charge amplifier and the output voltage recorded for various force inputs. The results for all 17 films are shown in Figure 2. As can be seen there is a linear relationship between the voltage and force as expected. It should however be noted that when measuring the vibration of the plate the output voltage will depend primarily on the d_{31} and d_{32} piezoelectric constants but measuring the d_{33} is easy and gives a good indication on the consistency of the sensitivities of the films. The average gradient of the data gave a sensitivity of 23.6 mV/N with a standard deviation of 0.77 mV/N. This is slightly lower than the specified value in the manual of 33 mV/N for a DT1 film [1].

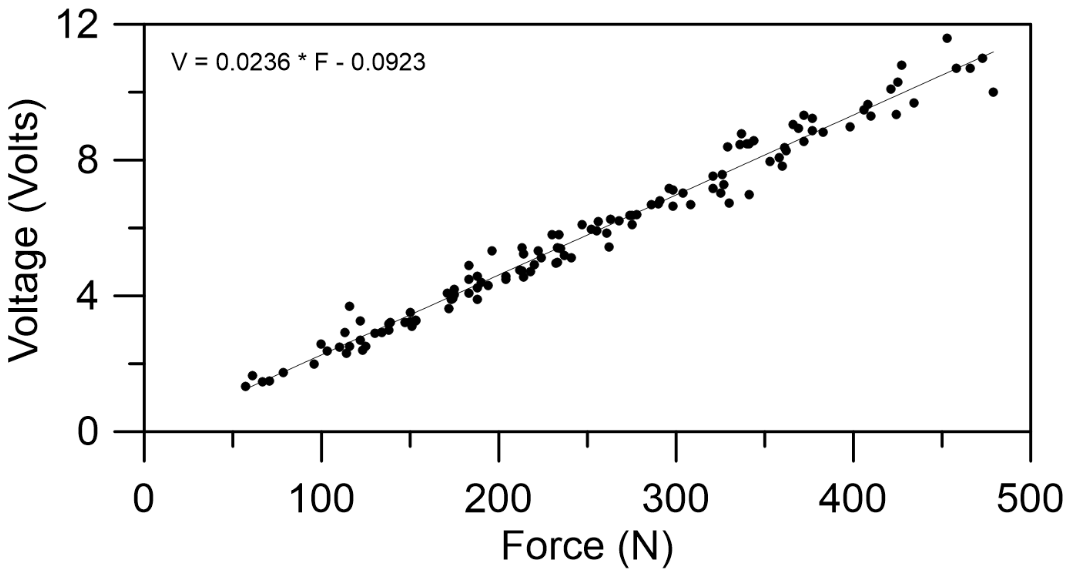

Figure 2. Calibration of the seventeen PVDF sensors used for the array

3. Modal Analysis

Figure 3a shows a photograph of the clamped plate setup. It consists of a 1.6 mm steel plate of radius 290 mm and mass of 3.25 kg. The plate is clamped on either side by two heavy (31.8 kg) steel flanges with an outer and inner radius of 290 mm and 206 mm respectively. The entire assembly was suspended from a wooden frame using four rubber springers. To excite the plate, a B&K 4810 shaker was attached to the centreline of the disc 145mm from the centre. A PCB 352C67 accelerometer was attached onto the steel plate 125mm away from the centre at an angle of 52^o from the vertical. A detailed vibrational analysis of this plate has been reported in previous work [7].

Seventeen PVDF sensors were attached to the surface of the plate covering the top quadrant of the disk as shown (sensors #1 to #17). These were attached using cyanoacrylate glue. Sensors #2 - #17 were aligned such that their 31 direction was parallel to the radius of the disk for all positions. Due to the central position of sensor #1 it was only possible to align its 31 direction parallel to the vertical radius.

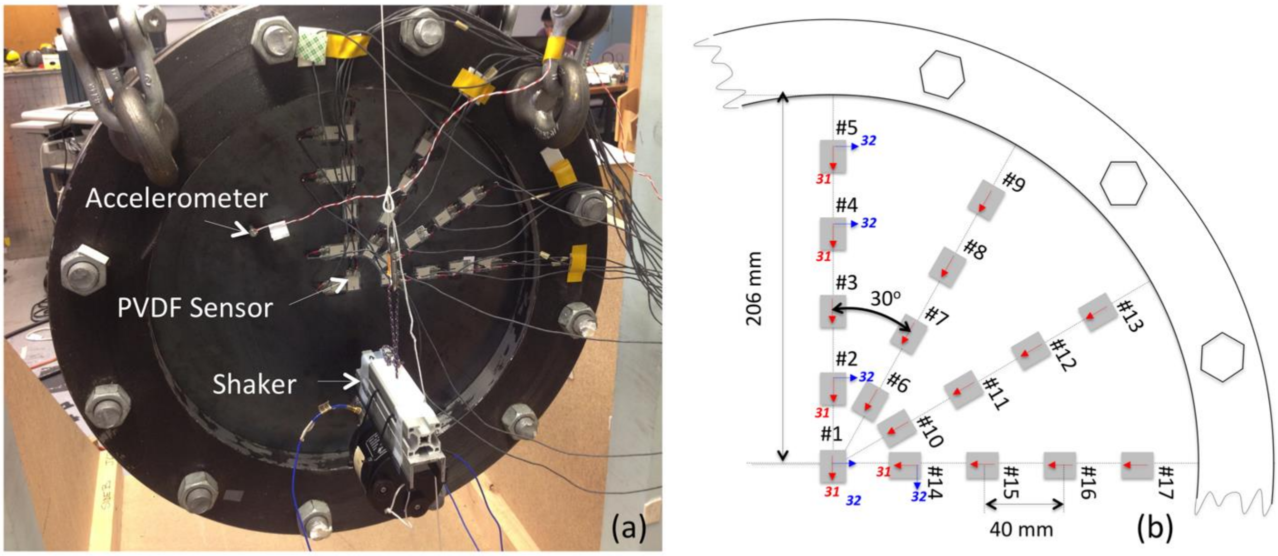

Figure 3(a) Photograph of the disk with 21 PVDF sensors attached to the back side. 17 sensors were aligned radially with four sensor aligned circumferentially. 3(b) shows the positions of the 17 radial sensors

The seventeen sensors were placed such that they formed four groups separated by 30^{o} with a radial spacing of 40 mm as shown in figure 3b. The signal from each sensor was amplified using a B&K 2635 charge amplifier and the frequency response measured for the first 1000 Hz using white noise. Figure 4 shows the frequency variation of the test point acceleration and the spectrum of the voltage output from PVDF film #4 for the first 1000 Hz. As can be seen, the PVDF film can be used to give the same results as a much more expensive accelerometer.

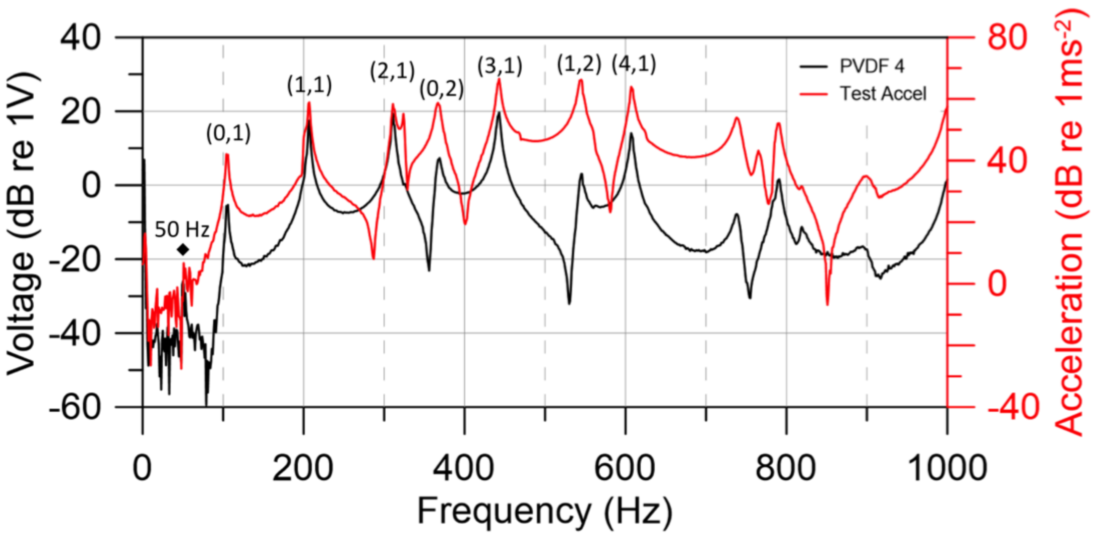

Figure 4. Frequency response spectrum from the test point accelerometer (red) and PVDF sensor #5 (black)

Table 2. The first 7 modal frequencies measured using the accelerometer and PVDF sensor #5

	Mode (0,1)	*Mode (1,1)*	*Mode (2,1)*	*Mode (0,2)*	*Mode (3,1)*	*Mode (1,2)*	*Mode (4,1)*
Freq.(Hz) Test Accel	105.5	206.2	312.6, 324.7	366.3	442.5	545.7	608.6
Freq.(Hz) PVDF	104.8	206.8	310.7, -	367.7	441.8	545.7	608.3

3.1 Laser Measurement

A Polytec scanning laser doppler vibrometer (SLDV) was used to scan the front of the disk at each of the first seven modal frequencies listed in table 2. The SLDV utilises a user defined grid of 409 points with a spacing of 0.0022m. To measure the normal surface velocity, the incident laser was set perpendicular to the surface of the plate at a distance of 1.3 m. The plate was excited by a single frequency sine-wave via a B&K 4810 shaker driven by a HP 8904A signal generator. Typical velocity readings from the SLDV ranged from 3.0×10^{-3} to 70.0×10^{-3} ms^{-1}. The output of each PVDF sensor was simultaneously recorded. Figure 6 shows the modal shapes obtained using the SLDV together with the relative positions of the PVDF sensors at each resonant frequency.(a) corresponds to f = 100 Hz, (b) = 201 Hz, (c) = 306 Hz, (d) =367 Hz, (e) = 443 Hz and (f) = 545 Hz.

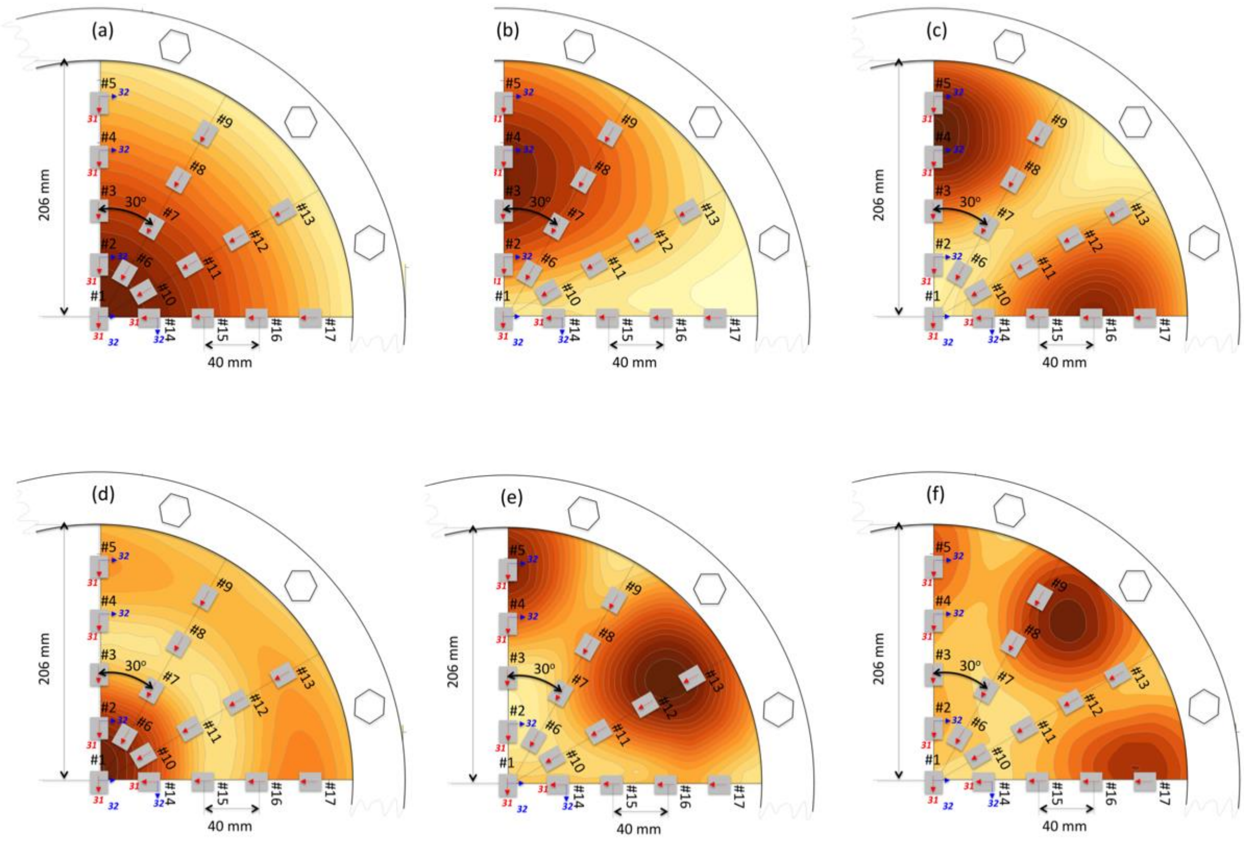

Figure 5. Modal shapes for the first six resonant frequencies obtained using the laser vibrometer. The positions of the seventeen PVDF sensors are also shown together with their orientation. (a) corresponds to f = 100 Hz, (b) = 201 Hz, (c) = 306 Hz, (d) =367 Hz, (e) = 443 Hz and (f) = 545 Hz

The charge generated on the PVDF sensor attached to the plate is dependent on the in-plane stresses that act on the sensor. From Figure 5 it is clear that the sensors will experience stress not only in their 31 direction but also in the 32. However, for the PVDF the 32 piezoelectric strain constant is approximately one tenth that of the 31 direction and can be considered negligible. Therefore the charge generated on the PVDF is given by $Q = d_{31} T$ where T is the average in-plane stress that acts on the sensor.

If there is a large variation in the stress over the length of the sensor then the sensor will measure the average stress across its length. This will be frequency dependent. As can be seen from figure 5, as the frequency increases the detail in the modal shapes also increases. In order to accurately capture this detail it is necessary to increase the number of sensors to compensate for the frequency increase.

3.2 PVDF Measurement

The voltage from each sensor was recorded for the first six resonant frequencies shown in Table 2. These voltages were contour plotted using Surfer. This is a contour and surface plotting package developed by Golden Software Inc. Contour plots were produced using the Kriging interpolation method. The results for the PVDF films are shown on the left side of the dotted line in Figure 6. The same method was used to contour plot the velocity data obtained using the SLV which were collected simultaneously on the front side of the disk. For the sake of comparison a mirror image of the laser data was produced and is shown on the right hand side of the dotted line in Figure 6. As can be seen there is very good agreement between the modal shapes obtained with the laser and that obtained with the PVDF sensors up to f = 443 Hz (e). For f = 545 Hz there is some discrepancy due to the fact that the PVDF sensor spacing is not small enough to capture the actual modal shape.

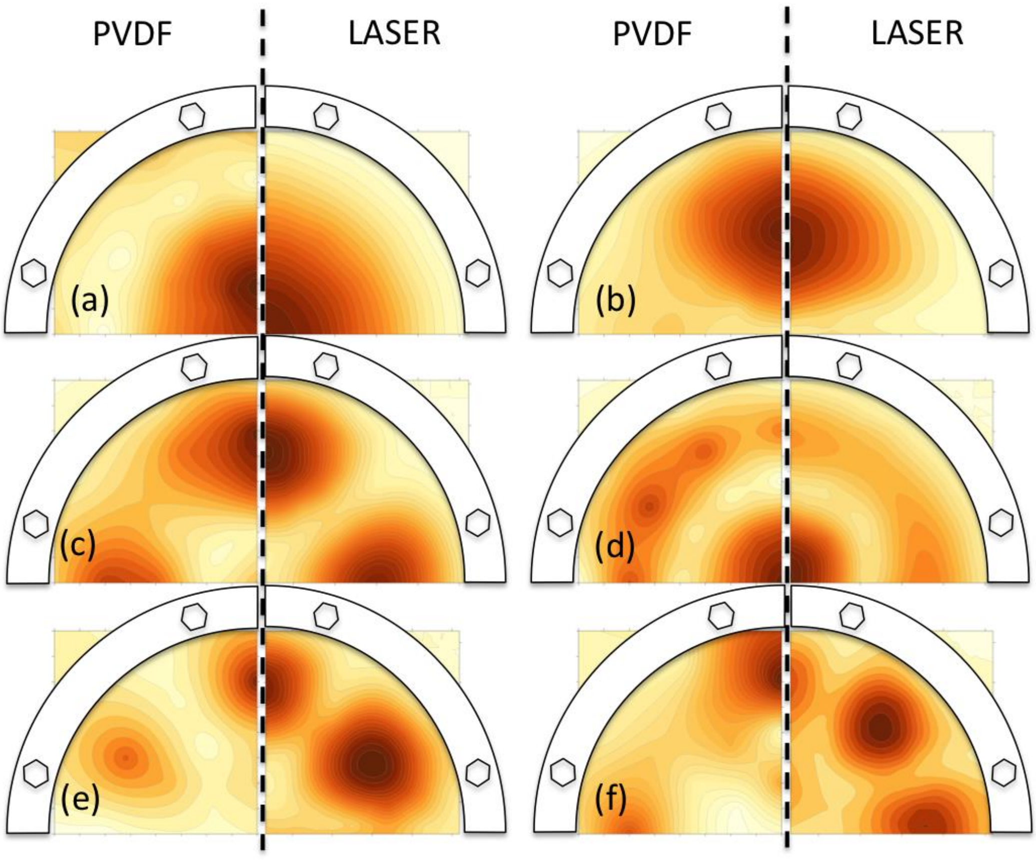

Figure 6. Comparison of the modal shapes obtained using the PVDF sensor array (Left side) and the SLVD (Right side). (a) to (f) correspond to the first six frequencies shown in Table 2

4. Conclusion

A PVDF array of seventeen sensors was used to accurately measure the modal shape of the first 5 modal frequencies (< 500 Hz) of a thin, rigidly clamped circular plate. Above 500 Hz the PVDF array failed to give correct modal shapes. The errors increased with increasing frequency and were due to spatial under-sampling of the PVDF films. By modifying as-bought films it was possible to significantly reduce electro-magnetic noise thus improving sensor performance in regions of low surface vibration. The PVDF film sensors could provide the same spectral information as a conventional accelerometer.

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