PERSPECTIVES ON IMMERSION THROUGH LASER DOPPLER VIBROMETRY

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ABSTRACT

Recording sounds from novel perspectives is of great interest in sound design. Sound design that provides a particularly immersive experience for the listener is increasingly relevant, with widespread use across music, film, computer games and other media modalities. Laser doppler vibrometry (LDV) is a non-contact technique for the measurement of mechanical vibration. LDV is used in a wide range of research and engineering applications, including biophysics, microelectronics, and the automotive industries. In audio and acoustics research, LDV can be used instead of piezoelectric transducers where high sensitivity, non-contact measurements are important to ensure the accurate capture of vibrations over a wide frequency range. However, while its use for data gathering and analysis is very well established, its potential as a creative tool in immersive sound design has seen very little research. In this paper we show that LDV can provide a unique and creatively valuable sonic perspective on sound making objects. We demonstrate how an LDV system can be optimised for such use, and allow high quality vibration recordings to be made and used in the creation of immersive sound and music experiences. The results build on what is possible with commonly used piezoelectric transducers by harnessing the non-invasive nature of LDV. The ability to measure vibration at a single point with very wide spectral resolution, and to focus on the vibration of both large and tiny objects, reveals a new sonic world with significant potential in the development of immersive sound design.

1. INTRODUCTION

'Immersion' has been used to describe many different ideas, technologies and experiences across a range of disciplines. However, there is an emerging consensus, discussed by Agrawal et al [1] in their literature review of immersion, that it is a phycological concept rather than being dependent on a particular technology or system. Murray [2] provides a helpful insight: '*Immersion is a metaphorical term derived from the physical experience of being submerged in water. We seek the same feeling from a psychologically immersive experience that we do from a plunge in the ocean or swimming pool: the sensation of being surrounded by a completely other reality, as different as water is from air, that takes over all of our attention, our whole perceptual apparatus*'.

When considering the relationship of sound to immersion there are many ways in which immersion can be achieved. This paper is concerned with the use of LDV as a way of creating sounds with an immersive quality to them and does so by addressing two ideas present in Murray's quote. The first is the idea of attention, where unfamiliar sounds have the capacity to facilitate an immersive experience for a listener as they seek to understand what they are listening to. The second is the idea that sound recorded with an LDV invites the listener to immerse themselves in the sound making object, the sonic experience presented is not that of airborne sound but the sound happening at the very surface of the object itself.

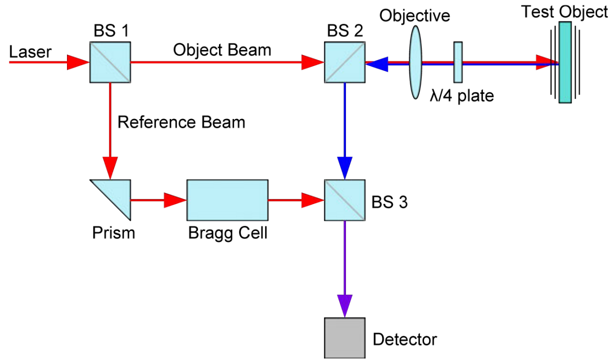

Figure 1. Schematic overview of an LDV system, such as the Polytec MSA-050 unit used in this paper.

2. OVERVIEW OF LASER DOPPLER VIBROMETRY

2.1 Interferometry

A laser doppler vibrometer is a device that uses laser light to measure out-of-plane vibration of physical objects, as illustrated in the schematic diagram in Fig. 1. Laser light, usually from a helium-neon (He-Ne) laser, is first split into two beams via beam splitter BS-1– the object beam, and the reference beam. The object beam is directed at a vibrating object and some of this light is reflected, or backscattered, back into the LDV optics and focussed onto a light-sensitive photo detector. Out-of-plane object motion (i.e., along the axis of the laser beam) imparts a periodically varying doppler frequency shift in this reflected laser light. The vibrometer optics, particularly beam splitters BS-2 and BS-3, compare this frequency-shifted light with the reference beam to determine the velocity of the test object at the measurement location. Fig. 2 illustrates the relationship between laser light, doppler shifted laser light, and the object velocity.

It is interesting to note that the He-Ne laser emits light of a frequency too high for the photo detector to respond to directly. However, the beat frequency between the object and reference beams, manifested as a light-dark interference pattern, is within the range of the photo detector and this results in an output that is proportional to the speed of the test object. While this arrangement provides a way to measure object speed, it cannot tell whether the object is moving away from the LDV or towards it, as movement in either direction will result in the same intensity at the photo detector. The speed-with-direction information, i.e., velocity, is in fact obtained through additional optics within the LDV, via the Bragg cell. This results in the LDV acting as an interferometer able to determine direction of object movement, also known as a heterodyne interferometer [3].

It is important to note that while velocity is most commonly obtained signal from an LDV system, other signal types can be derived through a variety of methods. For example, with an appropriate optical arrangement, surface displacement may be obtained via phase demodulation of the object and reference beams [3]. Alternatively, digital signal processing in the time or frequency domain can be used, as noted in section 4.8.

2.2 Non-contact surface measurement

The LDV method does not require any physical contact between the sensor and the object being measured, and this is one of its main advantages. Compared with other measurement techniques, such as the use of accelerometers, no additional mass is added to the test object which might influence its vibrational properties. Additionally, hot, lightweight, or moving structures where traditional contact-based instrumentation would change structural dynamics or be difficult to attach can be measured [4]. These advantages, together with excellent velocity resolution, and frequency resolution that can extend into the GHz range on some equipment, have led to its widespread use for vibration measurement. LDV systems are used in research across a diverse range of fields such as automotive engineering [4], biomedical research [5], Micro-Electro-Mechanical Systems (MEMS), and acoustics [6, 7].

This paper uses measurements made with a Polytec MSA-050 LDV system, which is based on a modified Mach-Zehnder interferometer, typical of most LDVs.

3. AUDITORY PERSPECTIVE

3.1 Defining auditory perspective

Given the ability of LDVs to accurately measure vibrations in objects, they are in theory well suited to capturing sound, albeit in a different way to conventional micro-

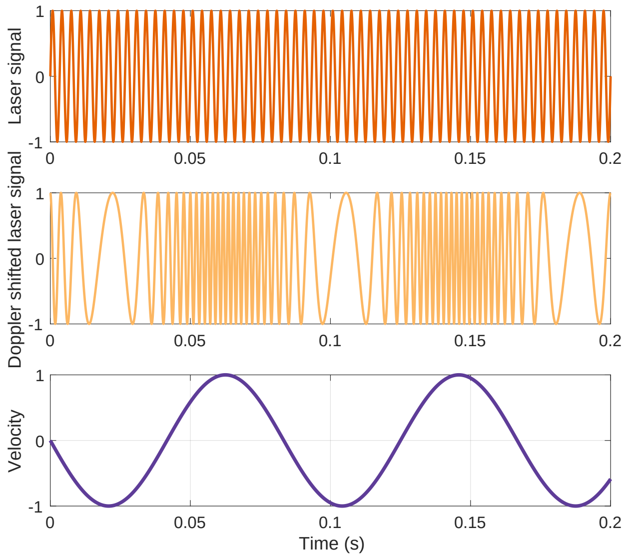

Figure 2. The LDV principle: A point of monochromatic laser light is targeted onto the surface of a vibrating object [top], causing the reflected laser light to be doppler shifted [middle], which is decoded with LDV optics and signal processing to give the out-of-plane velocity of the object at the measurement location [lower] – in this case, a 12Hz sinusoidal oscillation. The vertical axis units are arbitrary in these illustrative examples; similarly, the relative frequencies of object vibration and laser light are illustrative only, being much lower than in a real LDV system.

phones. When a sound making object is excited with energy it vibrates. These vibrations in turn move the air particles around the object causing sound waves to be transmitted through the air. These sound waves can be transduced into electricity by a microphone for recording. While both the LDV and microphone can be used to record the sound produced by an object, they are doing so in fundamentally different ways. The LDV will record the vibration of one specific point on the object's surface. The microphone will transduce the sound in the air around the object, which will be a combination of the sound radiating from all parts of the object (plus any reverberations). While it is possible to position the microphone closer to the object, it will never be able to capture the sound from a single 'point source' on the object's surface. This difference is of fundamental importance as it invites a change in perspective – a crucial aspect of sound recording.

Auditory perspective is the implied position of the listener relative to the sound source in a recording. Sound designer Karen Collins describes it as follows: '*Auditory perspective is constructed by a variety of techniques that create or reinforce the physical sense of space for the listener through the use of spatialized sound. These techniques combine physical acoustics with psychoacoustics*' [8].

3.2 Unusual auditory perspectives

Loosely defined, 'reverberation' is most often associated with perspective. However, it is instructive to consider

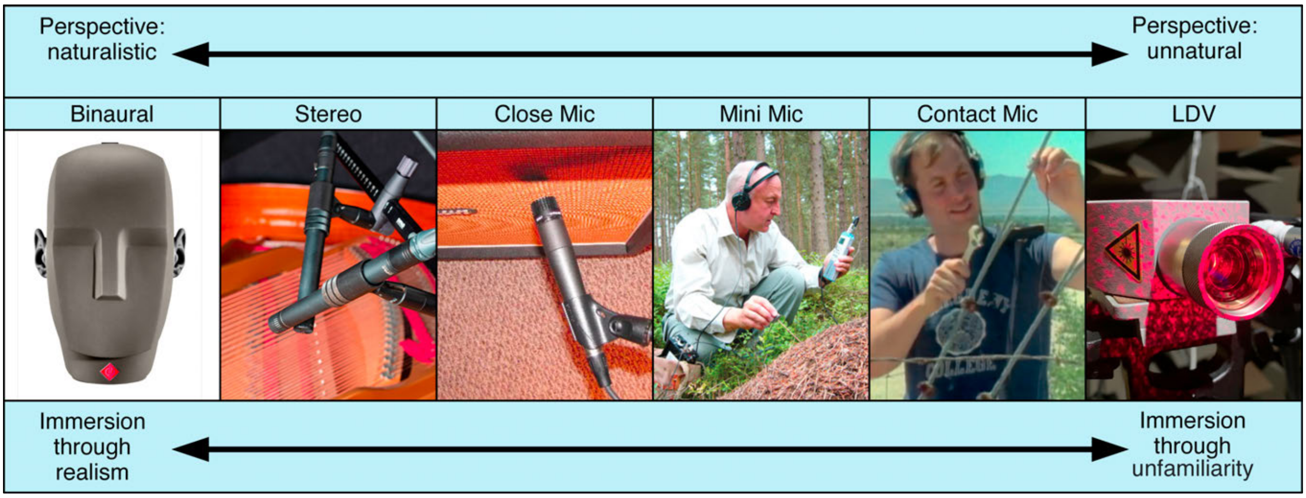

Figure 3. A notional organisation of perspective and immersion for sound design as a function of the audio acquisition tool, which illustrates at once the alignment between perspective and immersion, as well as apparent contradiction.

the contributory factors to reverb, such as echo timing and strength, frequency dependent damping, and channel width, occlusion, obstruction, and exclusion. Together these are interpreted by the listener to give an understanding of their spatial relationship with the sounds they hear. There are many recording and processing techniques, such as binaural and stereo, that aim to impart a realistic, albeit creatively manipulated, sense of perspective in order to define the relationship between the listener and the sound.

However, some audio practices have evolved that allow perspectives that are not recognisably human experiences. For example, sound recordist Chris Watson uses miniature microphones that can be positioned in very close proximity to the sound source of interest: '*When you get microphones in close, into places where you wouldn't want to or be able to put your ears, then the world is revealed in a very different way*' [9]. Watson has put this technique to creative use recording ant hills and glaciers from perspectives that are far beyond our experience as human listeners.

Contact microphones (usually constructed from piezoelectric accelerometers) are another recording method used to capture sound from an unusual perspective, this time from the surface of an object. This makes them relevant to discussion around sound capture using an LDV. The use of contact microphones has found its way into many sound practices including music, sound design, and sonic art. Composers seeking new sounds and approaches to performance embraced contact microphones from the 1950s onwards. John Cage's 'Cartridge Music' (1960) and David Tudor's Rainforest (1973) are early examples that use the distinct perspective afforded using contact transducers to shape and present sound in new ways. Pioneering sound designer Ann Kreober recognised the potential of contact microphones as a way of capturing unusual perspectives on often ordinary sounds: '*I attached the contact microphone to all sorts of things. It sounded as if you were actually inside the thing. As if you were inside a machine. When I attached the Frap* [contact mic] *to a ventilator, a whole new world opened up*' [10].

Kreober made extensive use of contact microphones for many projects including the sound design for the David Lynch film Dune (1984). Contact microphones have also been used by sound artists, such as Jez Riley French, who describes their creative use [11]: '*They reveal, with careful placement... a myriad of different acoustic textures, from the deep, subtle drone of metal structures to intricate movements of plants and insects. I'm fascinated by these hidden elements and the fact that every surface, every object is acting as a filter for the sounding world*'.

3.3 The LDV perspective

While contact microphones offer a unique perspective on sound which has a great deal of creative utility they do have some disadvantages. They add mass to the object they are attached to, and are typically flat and fairly large (circa 20mm diameter), making them awkward to attach to some objects. They are also limited in their frequency response, typically being focussed on the lower half of the human hearing range (up to about 10kHz) at the expense of the extremes of high and low frequencies. Noise can be an issue that limits the range of sources that can be captured. The use of the LDV offers a way to build on the perspective and recording abilities of the contact microphone, but adding value through being non-contact and wider bandwidth. This novel perspective may provide a rich source of audio for immersive sound design, as illustrated in Fig. 3.

4. PRACTICAL CONSIDERATIONS FOR THE USE OF LDV IN SOUND RECORDING

4.1 Introduction

Despite the many advantages of LDV systems in vibration and acoustics measurements, in practice a range of challenges are encountered. These challenges can be especially relevant in audio applications, such as in using LDV signals for immersive sound design. In this section, theoretical challenges around signal integrity and sources of

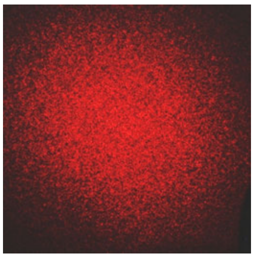

Figure 4. Speckle pattern produced by laser light focussed onto an on object surface [13].

noise are outlined, together with a summary of practical considerations that have been found to reduce or eliminate these issues. Although the LDV device used was a Polytec MSA-050, the challenges and mitigations presented here are universal to the basic method, and will likely apply to many models and implementations of LDV.

4.2 Speckle noise

In any audio recording context noise is present and where it is audible it needs to be managed to ensure usable sound recordings. For LDV applications the surface texture of the object being measured is closely linked to the signal to noise ratio achieved [12]. A major source of noise in LDV systems is that of speckle noise.

Speckle noise is not introduced from an external source but from the use of laser light itself. The coherent nature of laser light makes it an ideal light source for LDVs. However, when this light is reflected by an optically rough surface, where the surface roughness is approximately equal to or greater than the wavelength of the laser light (633nm for the system used here [14]), the result is a distinctive speckle pattern as shown in Fig. 4. The uneven surface scatters the light into wavelets with different directions. Where wavelets converge on the same point the path difference will determine the phase relationship of the detected light. Those in-phase will result in constructive interference and a light speckle, while those out of phase will result in destructive interference and a dark speckle. When the object vibrates the speckle pattern on the photo detector is constantly changing and this becomes a source of broadband noise in the decoded velocity signal.

4.3 Signal drop-outs

A more extreme form of noise exists under conditions where insufficient light is backscattered into the LDV optics, and the velocity decoder cannot determine the object velocity, usually for just a few samples worth of time. Instead, a drop-out occurs which is a brief loss of signal characterised by an audible click and distortion across the frequency spectrum; Fig. 5 provides an example from measurement of a vibrating cymbal head. Several factors may lead to a full drop-out occurring – see section 4.4.

In some measurement applications this behaviour is not overly problematic, but in applications involving audio playback for sound design purposes, it can be a significant issue. Practical setups should aim to minimise this behaviour as far as possible through ensuring strong signal integrity from the LDV unit.

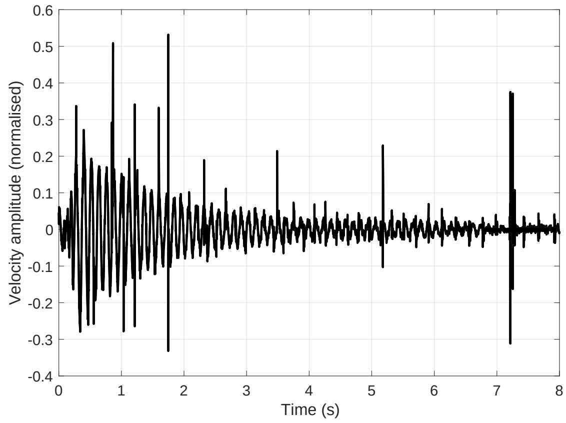

Figure 5. Signal drop-outs seen in an LDV measurement of a vibrating cymbal head. The random signal jumps are the drop-outs, caused by a temporary loss of backscattered light.

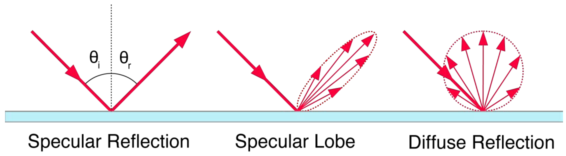

Figure 6. Three kinds of surface reflection that can happen when an LDV laser is focussed on a test object.

4.4 Surface reflection

While both speckle noise and drop-outs are distinctly different kinds of noise that occur for different reasons they share a common cause: the reflective properties of the sound making objects surface

Fig. 6 shows three different kinds of reflection, specular, specular lobe and diffuse. Highly reflective surfaces that produce a specular reflection are not ideal for LDV applications as the beam can easily be directed away from the LDV by the motion of the test object resulting in no signal at the detector. However, rough surfaces that produce diffuse reflections spread the beam over a wide area and result in not enough of the reflected light making its way to the LDV for a reliable signal with a high chance of drop-outs. Furthermore, any light that does make its way back into the LDV is likely to have phase discrepancies leading to speckle noise. A midpoint between these is ideal with a specular lobe reflecting most of the light into the LDV with some margin for additional movement helping to preserve the integrity of the signal. In practice this can be achieved by the use of retroreflective tape or the application of magnesium oxide powder to optically poor surfaces.

Fig. 7 shows a cymbal with a retroreflective tape applied to the surface to reduce drop-outs during recording.

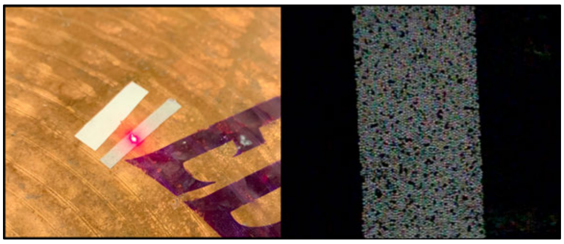

Figure 7. Retroreflective tape [left] applied to the surface of a cymbal, to reduce diffuse reflections (section 4.4) and speckle noise (section 4.2). A 1mm sized portion of the tape is shown through the on-axis LDV camera [right].

4.5 Pseudo-vibration

Pseudo-vibration is another source of measurement noise in LDV systems. Pseudo-vibration takes the form of contributions to the decoded velocity signal due to the laser beam 'scanning' across the optically rough surface of the test object as it vibrates in directions other than perfectly on-axis with the beam [15]. This causes a kind of periodic speckle noise (as per section 4.2) that can manifest as an otherwise plausible contribution to the velocity signal.

Reducing pseudo-vibration noise can be a challenge, depending on the nature of the sound making object. However, the following considerations have been found to be helpful when setting up a recording session for the purposes of capturing object vibration for immersive sound design:

1. When exciting sound from an object, consider the direction that the force or movement is applied and experiment with this. Some directions will usually lead to a similar sonic outcome but with reduced noise form pseudo-vibration.

2. The angle of incidence of the laser beam should be perpendicular, however, experience has shown that often a small repositioning can be enough to reduce noise. During recordings it has been advantageous to tripod mount the LDV sensor head to allow for flexible and stable positioning.

3. Clamping the test object to reduce movement other than the out of plane vibrations of interest helps to reduce the effect of pseudo-vibration noise. However, care should be taken not to dampen the sound of the object any more than is necessary.

4.6 Stand-off distance

Lasers tend to be thought of as sources of pure monochromatic light, but in practice this is not always true. In many cases lasers emit light of multiple frequencies, also referred to as laser modes. The cavity length of the laser employed by the MSA-050 LDV system in this paper is relatively short, and so in theory only one or a maximum of two laser modes are possible [14]. However, manufacturing tolerances, helium-to-neon ratio, pressure, and temperature all contribute to variation of the relative intensities of the two laser modes over time [16].

When setting up the LDV system for audio recording it is therefore best practice to choose a stand-off distance, d_s, that avoids any potential interference between the two laser modes; d_s is the distance from the head of the laser unit to the test object. The safest distances d_s to use are multiples of the laser's cavity length – 204mm in the case of the MSA-050. This distance is also known as the laser coherence repeat length, '*where the light frequencies emitted by the laser are all in phase*' [17]. For the MSA-050 unit, the smallest stand-off distance is 91mm - only possible with a microscope objective. The distances are then calculated by adding integer multiple of 204mm to this, giving optimal stand-off distances of 91mm, 295mm, 499mm and so on.

4.7 Focus

When setting up the LDV the laser should be accurately focused on the object in order to maximise the reflected light. This helps to ensure a good doppler signal at the detector and reliable results. However, there is a downside to sharply focusing the LDV, and that is that the speckle pattern of the reflected light will be at its most clearly defined and has the potential to produce more speckle noise (see section 4.2) as a result [17]. Consequently, in most practical audio recording situations there is a balance to be struck between a good signal level through accurate focus, and slightly defocusing the laser to produce an averaging effect on the speckle pattern which has the result of reducing speckle noise, and producing a cleaner velocity signal.

A related issue is that of optical depth of field, which is the distance range either side of the strict focus plane that is acceptably sharp and able to produce a sufficiently clear interference pattern within the LDV optics. The depth of field D of the LDV optics, in mm, is related to the stand-off distance d_s as follows [14]:

$$D = \pm \frac{d_s^2}{25000} \quad (1)$$

Note that this applies only when the microscope lenses are not being used. Increasing the stand-off distance can therefore be used to increase the depth of field and make measurements of objects with greater displacement ranges. Experience has shown that insufficient depth of field can lead to signal drop-outs (see section 4.3) and that moving the LDV head away from the test object to the next suitable standoff distance can improve signal integrity.

4.8 Types of output signal

4.8.1 Overview

As noted in section 2.1, the native signal type of LDV systems is usually surface velocity. Alternative signals, including displacement and acceleration, can be important in some engineering applications, such as setups also involving surface mount accelerometers; they can also be useful for audio applications. In this section, a brief summary of the issues involved in obtaining and using these alternative signals is presented, as well as brief reflections on relevance for capturing audio signals for immersive sound design.

4.8.2 *Obtaining displacement and acceleration signals from the velocity*

Some LDV devices, including the MSA-050 system used for this paper, can output signal types other than velocity, such as surface displacement, or surface acceleration. In a real-time context these signals can be obtained directly from an appropriate optical arrangement involving phase demodulation of object and reference beams [3], or via signal processing of the velocity signal. For the latter case, or where direct displacement decoding is not available, real-time applications tend to employ time-domain differentiation or integration of the velocity signal, usually in the discrete time domain. In offline applications, discrete frequency domain methods provide a convenient alternative approach.

Whichever method is used to obtain displacement and/or acceleration signals from an LDV setup, some general principles are of note in practical applications. Consider the mono-frequency vibration of a mechanical object, of velocity $v(t)$, amplitude A, and frequency f such that

$$v(t) = \Re(Ae^{i2\pi ft}) \tag{2}$$

where $\Re$ denotes taking the real part.

The displacement $x(t)$ is found via time integration as

$$x(t) = \Re\left(\frac{A}{i2\pi f}e^{i2\pi ft} + C\right) \tag{3}$$

for an arbitrary integration constant C, which can usually be ignored. Relative to the velocity, the displacement signal has an amplitude scaled by $1/2\pi f$. In contrast, the acceleration $a(t)$ is found, via time differentiation, to be scaled by a factor of $2\pi f$ (relative to velocity). Across all frequencies, this is equivalent to a 6dB/octave rolloff for displacement relative to velocity, and 6dB/octave gain for acceleration relative to velocity (see Fig. 8). In general, this means that an acceleration signal will be ‘brighter’ than a velocity signal, and a displacement signal will be ‘duller’, all else equal.

Where a velocity signal has been sampled digitally, frequency domain discrete integration/differentiation can be employed to obtain the displacement and acceleration signals [18]. Coding examples are available via section 6.1.

4.8.3 *Signal types for use in immersive sound design applications*

The previous sections 4.8.1–4.8.2 lead to a natural question when using an LDV the system to record sound – which signal should be used? As might be expected, the answer depends on the sound design goals of the given application.

In more conventional sound recording different microphone transducers have been developed that help to provide some context for these signals. Condenser microphones output a signal proportional to the displacement of the diaphragm, whereas ribbon and dynamic microphones output a signal proportional to the velocity of the diaphragm. In practice there is a complex interplay between the transducer type and the stiffness, damping and mass control of the diaphragm [19], as well as the accompanying electronics. While the ideal microphone would seem to require a flat frequency response this is technically hard to achieve and often creatively undesirable. Microphones will typically have a ‘sound’ that is imparted onto the recorded material primarily due to an uneven frequency response, whether the result of shortcomings or by design.

As with microphones where context and subjective goals will guide choice, our LDV recordings have shown that that both displacement or velocity may be chosen based on context. Our current practice is to capture both, although upon listening, there is usually a clear preference for the given application.

The difference between the displacement and velocity signals can be heard clearly in example recordings of a cymbal being gently struck – see section 6.1. The displacement signal has significant low frequency content from the surface vibration of the cymbal, whereas the velocity signal emphasises higher frequencies.

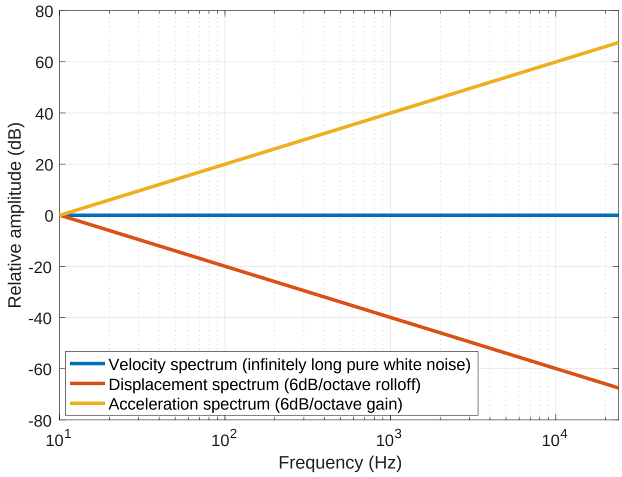

Figure 8. The relative spectral differences between velocity, displacement, and acceleration signals, for a hypothetical white noise velocity signal of infinite length.

5. LDV WORKFLOW FOR AUDIO AND IMMERSIVE SOUND DESIGN APPLICATIONS

5.1 Data format

Using a piece of equipment designed for scientific research presents several workflow challenges when attempting to use it for immersive sound design applications. The first is the ASCII file format used by the LDV acquisition software for data export.

The typical file format of LDV data can be seen in Fig. 9, which shows the MATLAB data import window for a displacement signal (column 2). To turn this into a format that can be used in sound design applications, the first step is to convert the data into a 16-bit signed audio file at the same sample rate the data was captured at, building in 6dB of headroom. In many cases it is useful to convert

	SourceFileName	Scan
	Number	Number
1	Source File Name:	Scan
2	Signal:	Time - Vib Displacement - Samples
3		
4	Time	Time Signal
5	[s]	[m]
6	0	-6.495247e-8
7	1.9531250437e-5	-5.389208e-8
8	3.9062500873e-5	-4.462201e-8
9	5.859375131e-5	-7.45105e-9
10	7.8125001746e-5	-6.162111e-8
11	9.7656252183e-5	-9.959821e-8
12	0.00011718750262	-2.084298e-9
13	0.00013671875306	-3.187229e-8
14	0.00015625000349	-1.2558e-7
15	0.00017578125393	1.600358e-8
16	0.00019531250437	-9.546134e-8
17	0.0002148437548	-9.8825e-9

Figure 9. File format of raw ASCII exported displacement data from the Polytec LDV software.

Figure 10. A practical example of the LDV in use for sound design applications: capturing the subtle mechanical sounds of a vibrating bike frame.

from the 51.2kHz sample rate of the Polytec platform to a more conventional 48kHz rate. Supplementary materials are provided via section 6 to demonstrate this via example MATLAB coding scripts.

5.2 Monitoring of signals during acquisition

A key issue when using the LDV to make audio recordings for use in sound design applications is that of monitoring. In conventional audio recording the signal of interest is carefully monitored in real time at the end of the signal chain, allowing any issues with the signal, either technical or aesthetic, to be addressed before a recording is made. However, monitoring on a system like the MSA-050 is limited to a crude 'level' reading of the Doppler signal strength, rather than giving the ability to instantly audition the signal from a qualitative standpoint. The only way to monitor the LDV output is to capture the data and then go through the conversion process established above and listen to the results.

To improve on the time-consuming process outlined above, a high-quality audio interface was integrated into the system. Instead connecting the LDV's decoded velocity (or displacement) output to the standard junction box, it is connected to the analogue line input of an RME Fireface UCX, which can accommodate levels up to +24dBu – equivalent to 12V, compared with the 10V maximum of the junction box. This offers a way to simplify the process as the signal can be digitised directly at a conventional audio sample rate, negating the need for sample rate conversion and data manipulation. Additionally, metering is accurate, making it easier and quicker to set the velocity or displacement range relative to the maximum input of the interface. The signal can be monitored on headphones, providing instant feedback on issues encountered when setting up. Speckle noise, drop-outs, and pseudo-vibration are all easily diagnosed and can then be addressed. Being able to hear the signal in real time is particularly helpful when focusing the laser and attempting to find the best balance between maximising signal level through sharp focusing of the laser, and defocusing to reduce speckle noise. In fact, this is such a quick and intuitive method that monitoring in this way may prove to be a beneficial addition to LDV setups even when audio recording is not the primary aim, given the sensitivity of human listeners in auditioning audio signals.

While this provides instant feedback and negates the need for conversion, the data export method is still relevant to future use cases where regions of the frequency spectrum above the capabilities of audio range converters are of interest. Automated gathering of measurements for multiple points is also more easily achieved using the full Polytec software package.

6. USE OF OF LDV-BASED AUDIO RECORDINGS

6.1 Audio quality and perspective

Using the methodology outlined above recordings of everyday sound making objects can be made. While care is needed to capture sounds with the system, tests have shown that in ideal situations, a signal to noise ratio of around 60dB is achievable. This makes recording for creative audio applications a realistic proposition.

The unique perspective offered by LDV has some similarities to contact microphone recording – the lack of any reverberation gives resulting sounds a remarkably close and immediate quality. However, the spectral resolution is much wider than can be achieved with a contact microphone and, subjectively, the recordings sound more detailed as a result. The non-contact nature of the technique makes it possible to record a wide variety of objects and materials. An illustrative example of a real-world sound design application is provided in Fig. 10.

Sound examples and coding examples can be found via:

- https://github.com/self-noise/SMC2024-LDV

6.2 Cost considerations

The cost of a typical LDV system is high when compared to more established recording tools, such as contact microphones, mics, and audio interfaces – the LDV system used in this work cost over €130k when new. This presents a barrier to widespread use for sound recording, at least when considering established delivery platforms.

However, technological advances mean that this cost will come down over time, and it is possible that a streamlined system, optimised for creative audio applications, could be designed at a significantly reduced cost. For example, as has been shown in section 5.2, conventional audio interfaces can be used to replace a significant portion of the signal acquisition system.

For the time being, the benefits of the technology and the perspective offered can be made available through the creation of sample libraries. Specific objects, themes, and recording approaches may be chosen to make the most of what this uniquely immersive sound recording approach has to offer.

7. CONCLUSIONS

In this paper we have shown that recording sound with an LDV system presents a range of technical challenges. In particular, the primary sources of noise – speckle noise, drop-outs, and pseudo-vibration – are fundamentally different to noise encountered in conventional sound recording. However, with an understanding of the operating principles and practical considerations, a working method has been established that allows high quality sound recordings to be made. In investigating the challenges involved and developing mitigations and working practices to overcome them, LDV can be used creative sound applications.

With an LDV, sonic artists can capture the character of vibration at specific points on the surface of a wide range of materials. An LDV brings perspectives that are not possible with contact or air-based microphones. As Kroeber pointed out with contact microphones, a whole new sonic world has opened up [10]. The sounds we have already captured reveal the immersive potential of this technique, bringing the ear closer to the sonic behaviour of materials that may be inaudible or impossible to capture otherwise. We see exciting potential to capture sound that may immerse listeners within unfamiliar contexts.

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