3D deformation and strain measurement of an intact eardrum using digital image correlation

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Abstract. In the field of hearing research, strain measurements are scarce. Such measurements can however provide valuable data on several middle ear pathologies. They could also help to gain a better understanding of the properties of the eardrum and further validate middle ear finite element models. We built a digital image correlation setup in order to assess three dimensional deformation and strain measurements of an intact eardrum. Different types of speckle pattern were evaluated. We then measured the deformation and strain of an eardrum subjected to large static pressures. The results illustrate that the application of digital image correlation to measure deformation and strain in intact eardrums is feasible. In the future, the setup will be further developed and eardrum strain measurements will be performed for different pathologies.

1. Introduction

Digital image correlation (DIC) is a powerful non-contact measurement technique allowing three dimensional local deformation and strain measurements. In engineering, the popularity of DIC has increased greatly over the last few decades. In the field of hearing research, the application of DIC is however still limited. DIC has been used to determine the mechanical properties of the stapedial tendon [1], anterior malleal ligament [2] and isolated strips of the human eardrum [3]. However, measurements on an intact eardrum have not been done before. Such measurements can provide valuable data on several middle ear pathologies.

The eardrum does not lend itself as an easy subject for DIC measurements. It is very thin and semi-transparent. The transparency can lead to light reflections from tissues behind the eardrum, resulting in correlation issues. Reflections can be avoided by first coating the eardrum with white paint, however, because the eardrum is so thin this should be avoided as the drying of the paint can affect the properties of the membrane. We will therefore investigate whether reflections actually degrade the correlation results when using a toner speckle pattern. We will also evaluate if reflections can be avoided when using fluorescent powder to generate a speckle pattern. This powder can be excited using laser light. Only the speckle pattern will then emit light of a longer wave length than the excitation source. By filtering out the laser light that reaches the camera, we avoid capturing any light originating from somewhere else than the speckle pattern, thus eliminating any reflections from behind the eardrum.

We will show full field displacement and principal strain maps for an eardrum subjected to high static pressures.
2. Materials and methods

2.1. Temporal bone & pressure generation
One rabbit temporal bone was used in this study. The middle ear cavity was opened, granting visual access to the eardrum from the medial side. The cochlea was removed, eliminating all fluid pressure effects on the ossicle chain. A plastic tube was glued onto the bony part of the ear canal. This tube was connected to a pressure generator, allowing us to pressurize the middle ear. We will refer to pressure as the applied pressure difference between the ear canal and the middle ear cavity. A negative pressure then signifies a lower pressure in the ear canal in comparison with the middle ear cavity.

Measurements were performed at positive and negative pressures of 0, 1, 2, 4 kPa. One full pressure cycle was performed. Several seconds passed between subsequent measurement steps.

2.2. Camera setup & software
Two cameras (Manta G-507, Allied Vision) with 2464 x 2056 pixels resolution were used. A lens (FL-CC7528-2M, Ricoh) and a 60 mm extension tube were mounted onto the camera. The cameras were placed at a 30° angle, approximately 12 cm from the temporal bone.

Images were processed using commercial software (ISTRÁ 4D, Dantec dynamics). The cameras were calibrated in the same software using a 5x5mm glass calibration plate (KL501005, Dantec dynamics).

2.3. Speckle pattern & illumination
Two types of speckle pattern materials were used. We applied toner and fluorescent powder to create speckle patterns (figure 1a and 1b respectively). Depending on the type of material that was used, different illumination sources were utilized. For the toner speckle pattern, we illuminated the sample with white light (KL 2500 LCD, Schott). When using the fluorescent powder, a 532 nm laser was employed as light source instead. Additionally, 532 nm filters were placed in front of the cameras. That way, the light perceived by the cameras could only originate from the fluorescent speckle pattern on the surface of the semi-transparent eardrum and not from reflections occurring behind the eardrum. Since only one sample was used in this study, both types of materials were applied to the same eardrum and measurements were performed for each.

Figure 1. Speckle patterns using (a) toner, (b) fluorescent powder
3. Results

3.1. Speckle pattern & correlation

Figure 2 shows photographs of the illuminated eardrum covered with a toner speckle pattern. The images show reflections originating from behind the eardrum. The locations of these reflections are not the same for both cameras. Reflections were not observed using the fluorescent speckle pattern.

Figure 3 shows the correlation agreement between the two cameras for both speckle pattern types. The correlation failed for four large zones in the image when using the toner speckle pattern. Three of these zones overlap with the locations of the reflections seen in figure 2. The correlation result obtained when using the fluorescent speckle pattern has only one zone missing due to a lack of speckles in this zone.

Figure 3. Representation of the correlation between the images of the two different cameras using (a) toner, (b) fluorescent powder. The red zones indicate a failed correlation due to different reflections reaching each camera resulting in very different gray values.
Figure 4 shows two photographs taken at different pressure steps. We see that the reflection spots move relative to the speckle pattern.

![Figure 4](image)

**Figure 4.** Relative movement of reflections originating from behind the eardrum to the toner speckle pattern between pressure steps (a) +1 kPa and (b) +2 kPa (Camera 2).

3.2. **Displacement**

Figure 5 shows the full field Z-displacement when the eardrum is exposed to different static pressures. The fixed edge of the tympanic membrane is correlated as well, indicated by the non-moving boundary in the image.

Figure 6 shows the Z-displacement for a single point of the eardrum. We can see a hysteresis occurring when the eardrum undergoes a full cycle of the applied pressure steps. The displacement is slightly larger in the negative Z direction.

![Figure 5](image)

**Figure 5.** Interpolated full field Z-displacement shown for different applied static pressures.
3.3. Principal strains

Figure 7 shows the first principal strain of the eardrum for an over- and underpressure. The principal strain direction for overpressure is circumferential. The magnitude varies between 0 and 40 millistrain. The strain in the case of underpressure is almost zero.

![Figure 7. First principal strain magnitude and direction for (a) +4 kPa, (b) -4 kPa](image)

4. Discussion

4.1. Speckle pattern & correlation

We see that different reflections, originating from behind the semi-transparent eardrum, are observed for each camera when using the toner speckle pattern (figure 2). This will result in very different grey values in some areas of the image for each camera. This results in failing of the correlation algorithm for these areas (figure 3a). Similarly, for a single camera, the reflections move relatively to the speckle pattern when the eardrum deforms (figure 4). The correlation between images at different pressure steps from one camera will not succeed. As a consequence, the displacement cannot be calculated in these areas.
Using the fluorescent powder in combination with the laser illumination and filtering solves this problem (figure 3b). Although a different face size and spacing was used, it is clear that there are no big missing zones due to reflections as there are no reflections possible.

The eardrum could also be coated with a white layer of paint after which the toner could be applied. However, since the eardrum is so thin, we avoid using a full layer of paint, which will dry up and might stiffen the eardrum.

4.2. Displacement
We can see from the full field Z-displacement that the deformation of the eardrum is quite uniform under static loads. The areas between the malleus and the eardrum edge are slightly more mobile, as expected (figure 5).

The single point displacement illustrates the typical hysteresis loop associated with the viscoelastic properties of the middle ear system (figure 6).

The mobility is higher for negative pressures than for positive pressures. This is as expected, as the membrane stretches when being exposed to positive pressures, but ‘collapses’ when being subjected to large negative pressures. However, from Dirckx [4] we know that this asymmetry of the displacement curve should be larger. It is possible that air leakage occurred during the experiment. Our future experimental setup will include an extra pressure measurement in the ear canal to ensure that the desired pressure is actually applied to the eardrum.

4.3. Principal strains
As mentioned in section 4.2, the eardrum stretches when being subjected to large positive pressures but not so much when undergoing large negative pressures. This can be observed when looking at the principal strain (figure 7). A nonzero strain exists when applying an overpressure, but the strain is nearly zero on the entire membrane when applying underpressure.

We can see that the direction of the first principal strain for overpressures is circumferential. This may be due the lesser movement of the superior part of the membrane (top of the image).

5. Conclusion
A DIC setup was built capable of measuring deformation and strain in an intact eardrum. Toner and fluorescent speckle patterns were compared regarding correlation issues. It has been found that fluorescent powder works better to avoid reflections.

Future work will involve further development of the setup and measuring eardrum strain under static and dynamic loads of middle ears with different pathologies.

References
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