High Speed Photography as a Tool for Musical Instrument Research

Citation for published version:
Woolley, A, Campbell, DM & Lopez-Carromero, A 2018, 'High Speed Photography as a Tool for Musical Instrument Research' Proceedings of the Institute of Acoustics, vol 40, pp. 370-379.

Published In:
Proceedings of the Institute of Acoustics

HIGH SPEED PHOTOGRAPHY AS A TOOL FOR MUSICAL INSTRUMENT RESEARCH

A Woolley University of Edinburgh, Edinburgh, UK
DM Campbell University of Edinburgh, Edinburgh, UK
A López-Carromero University of Edinburgh, Edinburgh, UK

1 INTRODUCTION

Much of the behaviour of musical instruments involves vibrations and other motions that are too rapid to be followed by the human eye. These can, however, be visualised with the slowed down replay from a high speed camera. This technique has been used in Edinburgh over many years to study a range of instruments in order to improve their playing and manufacture. Recently, the incorporation of Schlieren optics has made it possible to directly visualize high amplitude sound waves as shades of grey. This paper describes a number of these applications including studies of the lips of brass players, the shock waves from the end of a trumpet bell, the vibration of double reeds and the bow/string interaction of viols. High speed photography has also been used to study the simultaneous movement of the key and pallet of a mechanical action pipe organ as part of an ongoing project, partly funded by the Arts and Humanities Research Council, investigating whether the player is able to influence the transients by varying the movement of the key with the aim of better understanding the most musical, mechanically efficient and cost effective type of pipe organ action.

This paper describes the equipment used to make high speed recordings and discusses some of the problems encountered and how they were resolved.

Not all applications lend themselves to reproduction in a printed paper, however individual frames from three of the projects are presented in a way that clearly illustrates the effects observed and how they can be related to other measurements.

2 HIGH SPEED CAMERA EQUIPMENT

2.1 Hardware

The high speed camera currently in use is a Photron Fastcam SA1. This can record up to 675,000 frames per second (fps) with a slowest shutter speed equal to the reciprocal of the frame rate. The maximum resolution is 1024x1024 pixels which is available up to 5,400 fps. This reduces to 64x16 pixels at the maximum frame rate.

The lens in use is a Nikon Nikkor 24-85mm f2.8-4 macro lens. This allows a field of approximately 5x5cm to be viewed full frame.

Two types of lights are used:

i. Arrilux 125 incandescent spotlights which provide an intense and even field but run hot and are unsuitable for use close to players' bodies both because of the heat and because of the danger of failing bulbs

ii. Jansjo led spotlights from IKEA which are small, are mounted on flexible stalks, run cool with no danger of explosion, give an even field and are flicker free. Although they have a limited light output, their low price, small size and ease of placement means that multiple lights can readily and advantageously be used.

2.2 Software

The software used is Photron Fastcam Viewer provided by the camera manufacturer. This allows for extensive manipulation and editing of the images. The default Windows video viewer operating at 30fps is very useful for quickly viewing recordings.

3 APPLICATION OF HIGH SPEED PHOTOGRAPHY TO MUSICAL INSTRUMENT RESEARCH AT THE UNIVERSITY OF EDINBURGH

High speed camera use at The University of Edinburgh, dating back to 2001, has been applied to study a number of aspects of musical instruments. The main subjects for research have been: lips of brass instrument players, shock waves from brass instrument bells, relative movements of the key and pallet of a mechanical pipe organ action, vibration of double reeds, vibration of organ pipe reeds and bow string interaction in viol playing. The first three of these are used as examples demonstrating the use of different frame rates

3.1 LIPS OF BRASS INSTRUMENT PLAYERS

In order to study the movement of the lips of a brass instrument player it is obviously necessary for the camera to have direct sight of the lips. In order to achieve this, a plastic mouthpiece was made with a clear window opposite the lips and the connection to the body of the trombone at one side. This can be seen in Fig 1 which also shows the camera and the flexible LED lights.

A recording speed of 5,000 fps was used to record the player playing B_b2, approximately 116Hz. Alternate frames from this recording are shown in Fig 2. The frames are therefore 1/2,500 second apart.

It can clearly be seen that the movement of the lips is complicated. The motion is three dimensional and a wave moving from left to right is visible on the lips of this player. In order to calculate the area of the lip opening in two dimensions, black and white video recordings have been analysed frame by frame using Matlab image analysis software.

Colour images are used partly for visual effect but monochrome images may allow easier analysis of low contrast subjects.

Fig 1. Photographing trombone player’s lips showing the high speed camera, the transparent mouthpiece with the trombone body attached to the right side and LED lights.

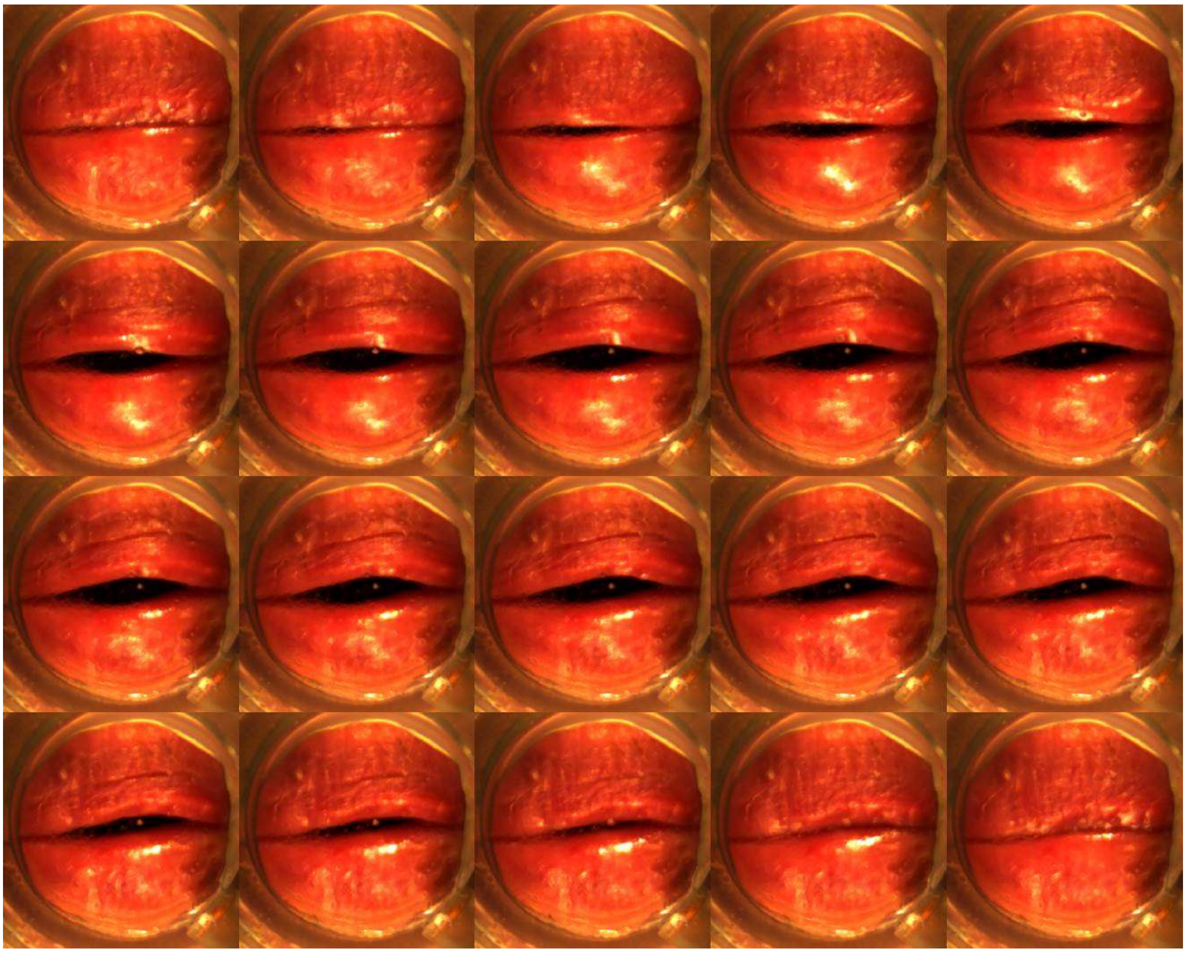

Fig 2. Frames from the recording of the trombone players lips at 1/2,500 second intervals running from top left to bottom right

3.2 Wavefront from a trumpet bell

As part of a larger project[1,2], it was necessary to visualise the wavefront of sound radiated from a trumpet bell in order to validate calculated predictions. As the wavefront is not visible to the naked eye, Schlieren techniques were used to show the variation in density of the air due to the shock wave (Fig 3). A point light source is shone at a spherical mirror and the reflected rays are deflected so as to form a point on the edge of a knife edge. If the beam is deflected to the right, less of the beam will be obscured by the knife edge and the image will become lighter, if it is deflected to the left, more of the beam will be obscured and the image will become darker. The trumpet bell is placed to radiate its sound across the light beam just in front of the mirror. The recording was made at 75,000 fps.

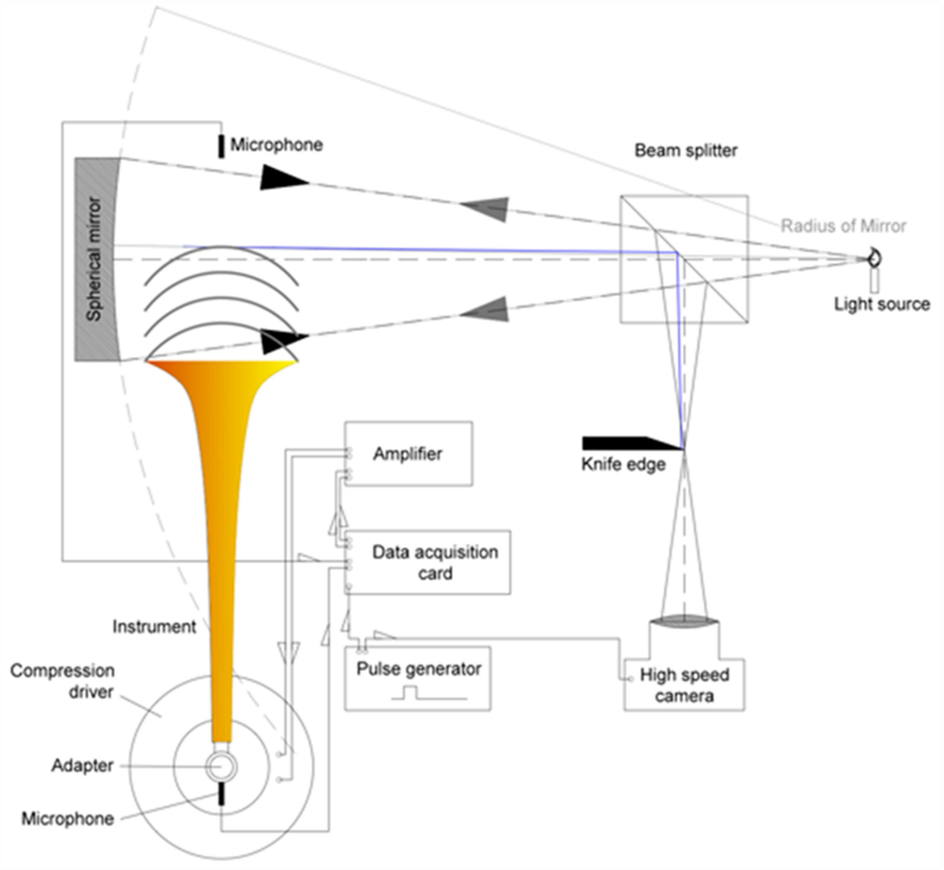

Fig 3. Schematic diagram of the Schlieren apparatus used to investigate the wavefront from a trumpet bell.

Fig 4 shows every fourth frame from the recording of one complete wavefront, i.e. at intervals of 1/18,750 second.

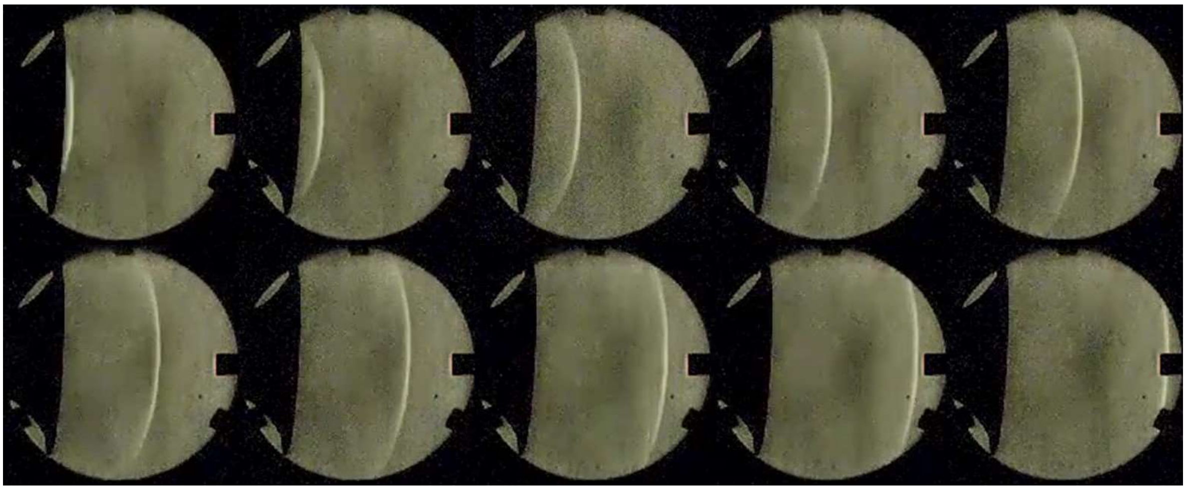

Fig 4. Wavefront from a trumpet bell at intervals of 1/18,750 second. The trumpet bell is on the left and the circular object in the background is the mirror on the left of Fig 3

3.3 Mechanical pipe organ actions

The Group has been investigating the relative movement of the key and pallet valve in mechanical action pipe organs (the movement of the key is transmitted to the pallet by purely mechanical means) in order to determine to what extent the player can influence the transients by the way that they move the key[3,4]. A cross section of a typical mechanical windchest is shown in Fig 5.

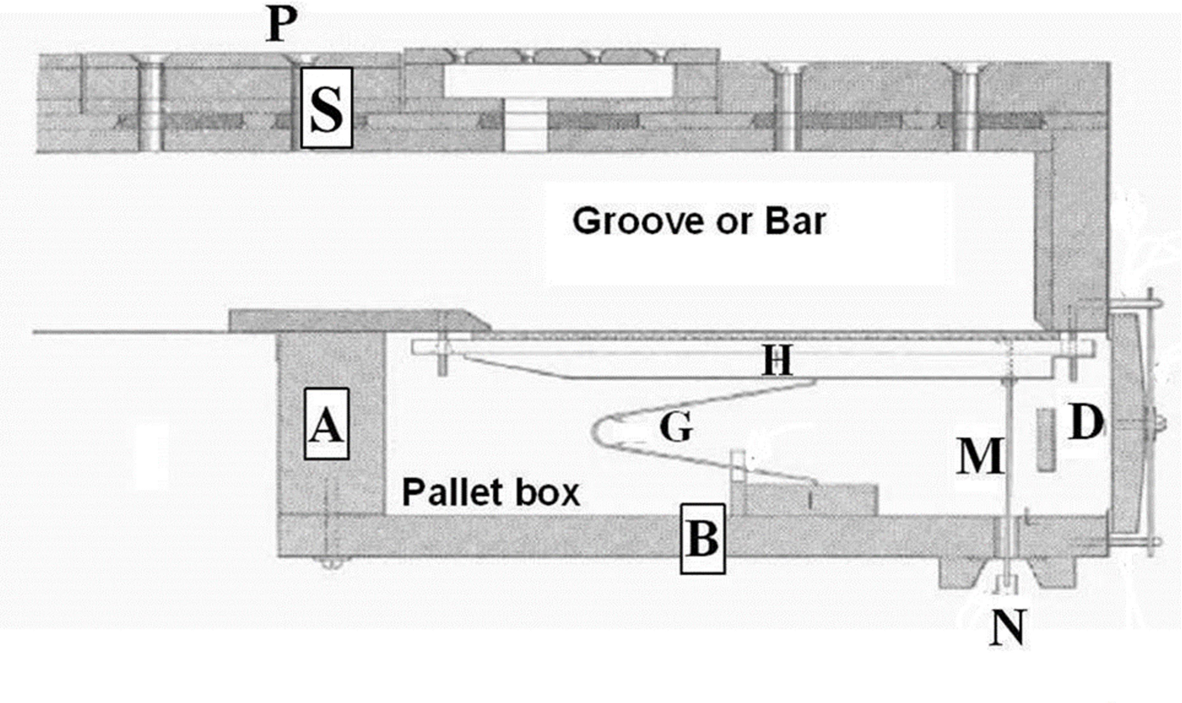

Fig 5 Cross section of a bar (groove) and slider windchest adapted from Audsley Fig. CLIX[5]. The significant parts are: N connected to the tracker from the key and pulling open pallet H via tracker M, compass spring G providing the closing force on the pallet, pallet box ABDH containing pressurised air, groove or bar connecting all pipes played with one key (atmospheric pressure when the pallet is closed), slider S shown open so that the pipe, planted in tapered hole P, will speak when the pallet H is opened

The key is connected to the pull down N by a system of levers, trackers and rollers. These are illustrated and explained in Fig 6.

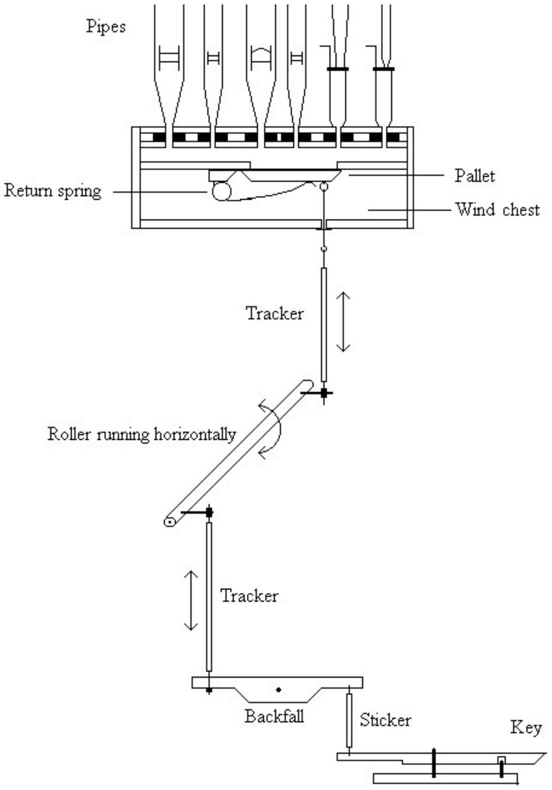

Fig 6. Diagram of the mechanical link from the key to the pallet. The key and backfall pivot, trackers pull when the key is pressed down, stickers push and rollers transmit the motion horizontally[6].

At rest, the pallet box ABDH contains pressurised air and the groove, controlling all the pipes played by one key, contains atmospheric pressure air. The pipes are placed on tapered holes P and ranks of pipes are turned on and off by sliders S running perpendicular to the diagram. The pallet valve H is kept closed by the spring G and the force on its underside from the pressurised air in the pallet box. In order to open the pallet the force due to the spring and the pressure on its underside has to be overcome. Immediately the pallet starts to open the pressures above and below it equalise and the force required to move the key further suddenly reduces. This effect is known as pluck (analogous with harpsichord pluck) and has been likened to pushing the finger through a thin sheet of ice. As it is not possible to make the action run from the key to the windchest completely rigid because of the need to keep key forces to a comfortable level, the action components bend and twist and thus act like a spring. The key will move a significant distance before the pallet starts to open at which point it "catches up" with the rest of the action. Combined with the reduced key force at this point, control of the pallet and thus transients would be very difficult. Throughout this project the time of movement of the pallet was consistently around 30ms. Landry and Champoux[7] showed that the best reaction time of a musician was 170ms and is thus unable to react to the pluck in order to reduce the force being applied to the key. The high speed camera, operating at 1,000fps, was used to visualise the initial opening of the pallet relative to the key movement using a system of periscopes.

Fig 7 shows the camera in place in front of the model organ. The windchest is at the top with a clear plastic window in place of the front board D from Fig 5. A system of mechanical levers leads to the keys at the bottom of the model. The mirrors on the left show the movement of the key and the mirrors on the right allow a simultaneous view of the front of the associated pallet.

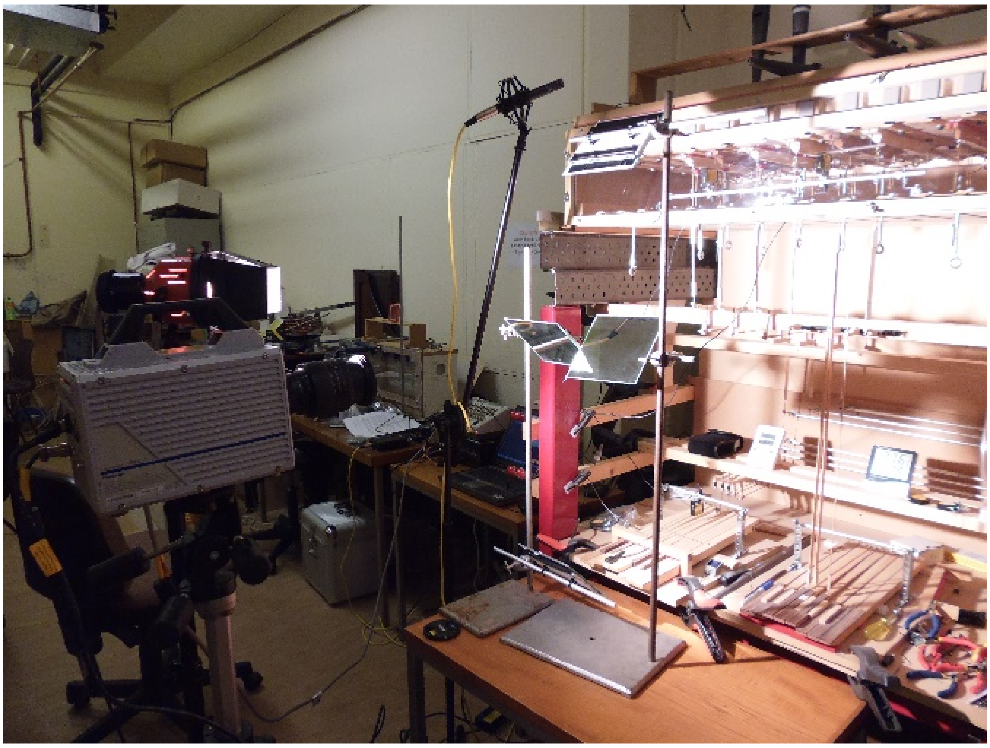

Fig. 7. Camera in front of model organ with mirrors to get images of key and pallet in the same frame

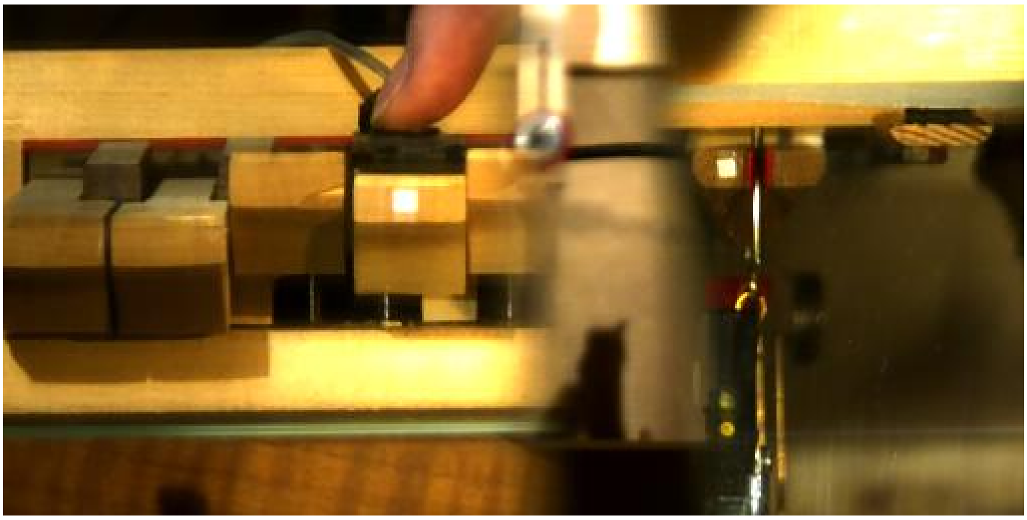

Fig 8. Full image from one frame of recording showing key on left and corresponding pallet on right

Fig 8 shows a sample frame with the key on the left and the pallet on the right, both marked with white squares. The key can be seen to be depressed a significant way with the pallet still closed. There is a force sensor between the finger and the key top.

A screwjack was used to move the key as smoothly as possible over a period of approximately four seconds from rest to fully depressed. Fig 9 shows measurements of the movement using position sensors, pressure sensors and a force sensor. The blue line is the movement of the key. The red line is the movement of the pallet which can clearly be seen to open suddenly at about 1.2s allowing the pressure (purple line) to rise rapidly causing the pipe to speak cleanly. The force exerted by the key (green line) can be seen to drop at the pluck point. The pallet can also be seen to close in advance of the key on release resulting in a rapid ending of the pipe speech. The units on the vertical axis are arbitrary.

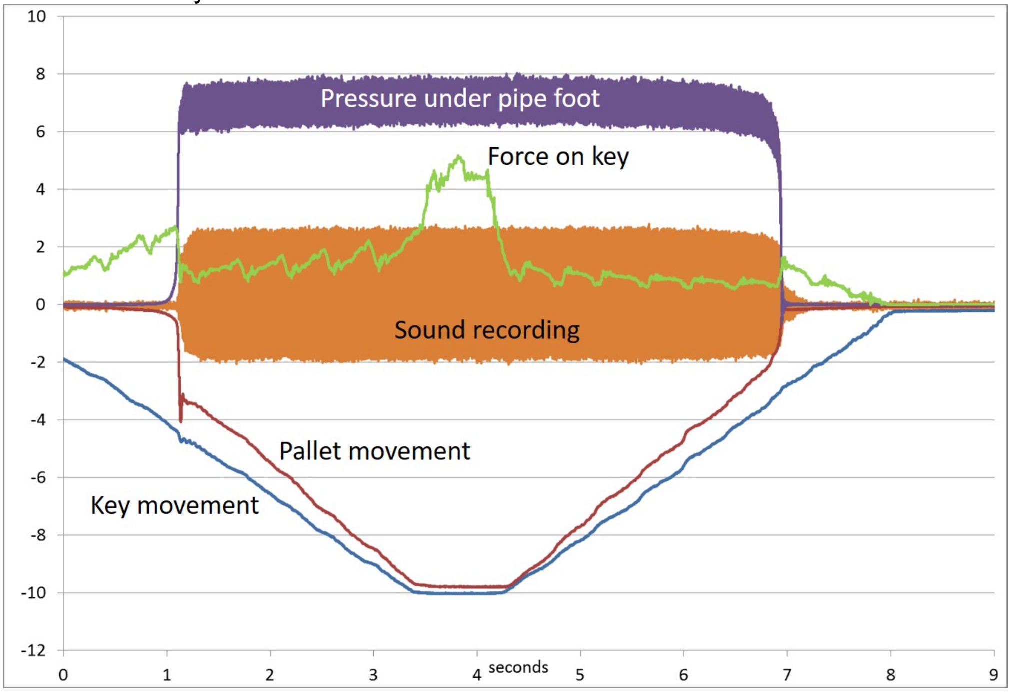

Fig 9. Key moved by screw jack. Graph showing key movement (blue), pallet movement (red), pressure at pipe foot (purple), force applied to key(green) and sound recording (orange).

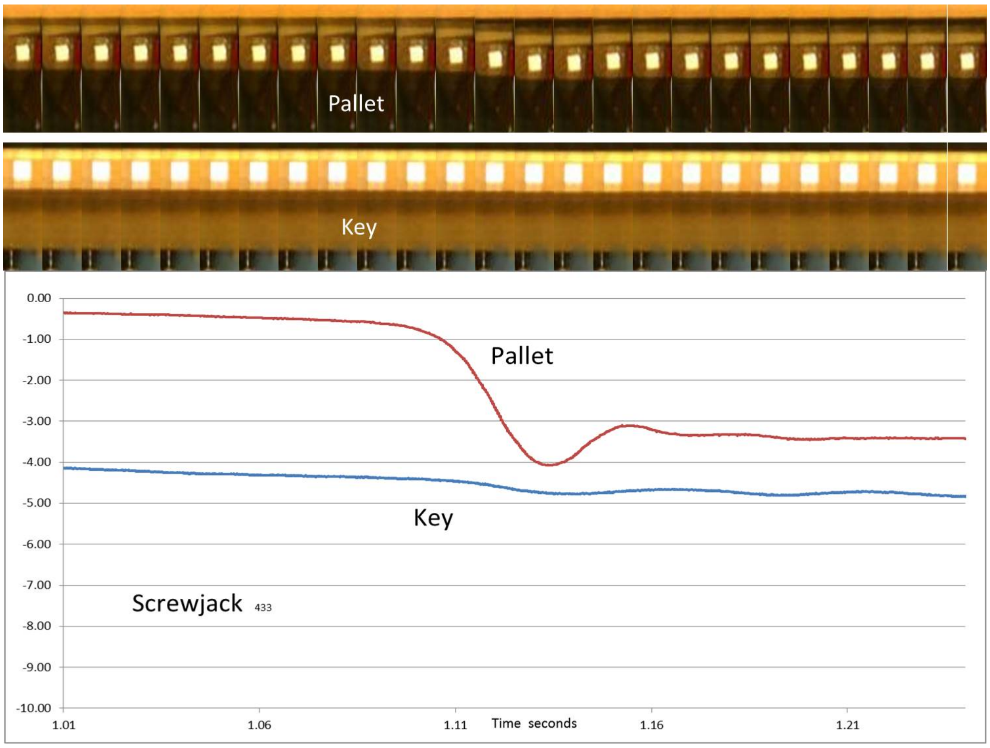

Fig 10. Point of pallet opening from the recording of the key being moved by screwjack. Photographs at 1/100 second intervals. 0.00 on the vertical axis represents the key and pallet rest position and -10.00 represents the key fully depressed and the pallet fully open.

Fig 10 shows the frames covering the initial opening of the pallet aligned with the corresponding extract from Fig 9. The key started at point zero on the x axis. The images are at 1/100s intervals.

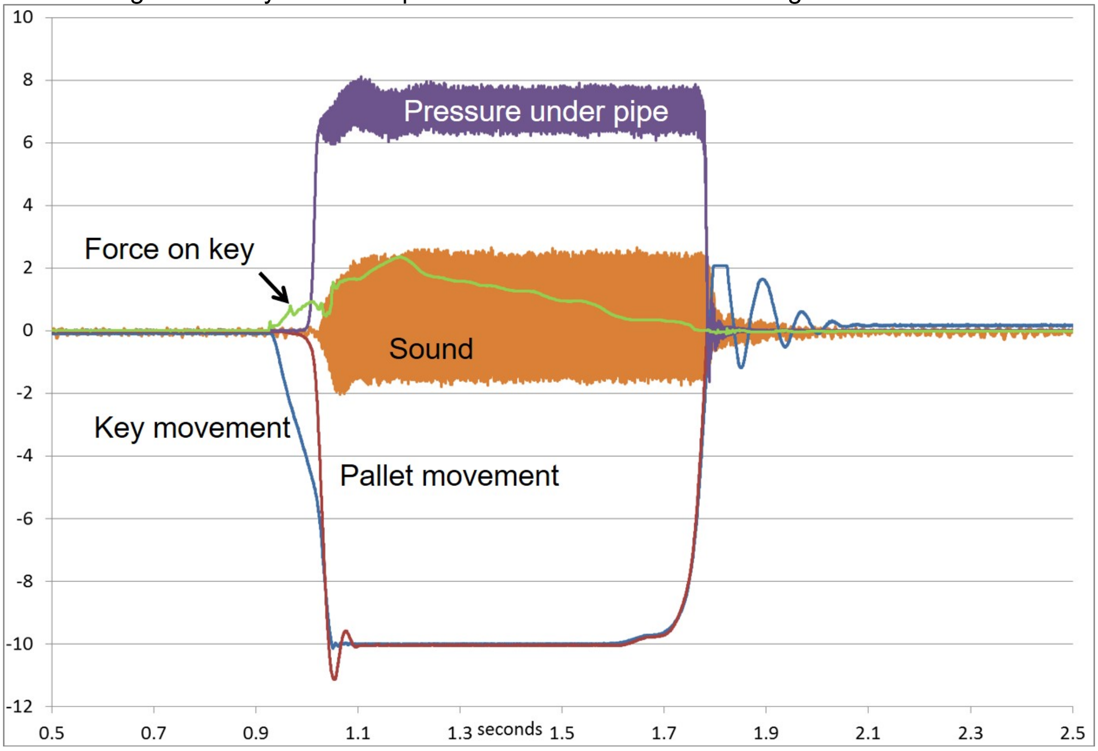

Fig 11. “Fast” key movement. Graph showing key movement (blue), pallet movement (red), pressure at pipe foot (purple), force applied to key(green) and sound recording (orange).

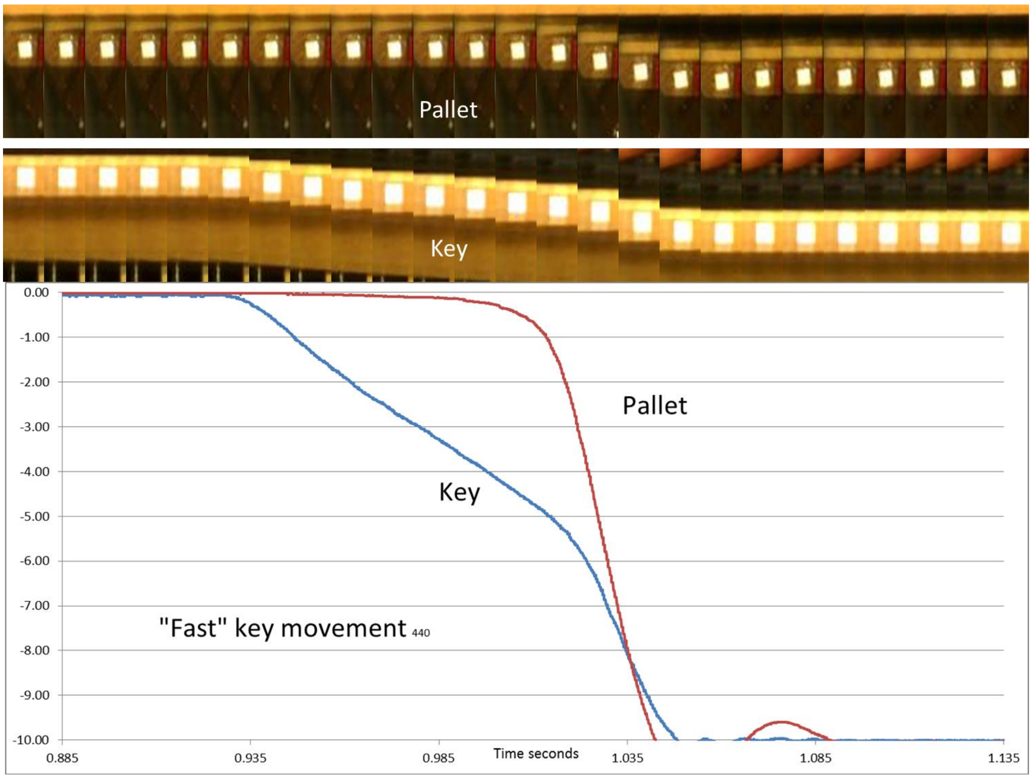

Fig 12. “Fast” key movement. Graph showing key movement, pallet movement, pallet box pressure, pressure at pipe foot, force applied to key and sound recording.

Figs 11 and 12 show the same information for a “fast” finger movement of the key. Fig 11 is not to the same time scale as Fig 9 whereas Figs 12 and 10 are. The effect of the flexibility in the action is still visible with the pallet starting to open at the same point in the key travel which can be seen to slow down as the resistance due to the flexing of the action increases. The low frequency variation in the pressure is due to a lag in the pressure regulator.

Whilst there is a small audible difference between the transients when directly compared, it does not reflect the extreme difference in key movement, which would not be encountered during normal playing.

The equipment used for measurements was:

Key and pallet movement – laser distance sensor Baumer OADM12U6430/S35A
Pressure measurements – Sensortechnics HCXM020D6V
Force sensor –Sensym FS1
Data acquisition hardware – Iotech Wavebook 516E
Data acquisition software – Iotech Waveview 7.15.19

4 CONCLUSION

This paper illustrates a variety of ways in which high speed photography can be applied to musical instrument research using a wide range of frame rates. Musical instruments encompass mechanical movements as well as acoustic waves and photography can be used to investigate all aspects. In some instances, it is only by studying such images that it is possible to understand the processes that are taking place which may not be as simple as expected, for example the shape of the trombone player’s lips. The need for high illumination at high frame rates because of the associated short shutter opening is a significant factor in designing experiments particularly when players are in close vicinity and this can be the limiting factor for safety reasons. A further factor to be borne in mind is that at high frame rates the data files can be very large, frequently several gigabytes, which can lead to difficulties in processing, transfer and storage.

5 REFERENCES

1. López-Carromero, Amaya; Campbell, D. Murray; Rendón, Pablo Luis and Kemp, Jonathan. *Validation of brass wind instrument radiation models in relation to their physical accuracy using an optical Schlieren imaging setup.* 22nd International Congress on Acoustics, Buenos Aries, Argentina, 5-9 September 2016
2. The research leading to these results has received funding from the People Programme (Marie Curie Actions) of the European Union’s Seventh Framework Programme FP7/2007-2013/ under REA grant agreement No. 605867 supporting the BATWOMAN ITN Project, and DGAPA-UNAM via its support of the PAPIIT IN109214 Project.
3. Woolley, Alan. *The Organ: A Dangerously Inexpressive Musical Instrument?* (The Diapason, October 2013. Scranton Gillette, Arlington Heights IL
4. Woolley, Alan and Campbell, Murray. *A musical and mechanical study of tracker actions* (ISO Journal, No. 56, August 2017 pp 5-40. ISO Lauffen, Belgium)
5. Audsley, George Ashdown. *The Art of Organ Building* (Mineola, Dover 1965 republication of 1905 edition, Dodd, Mead & Co)
6. Pykett, Colin. The Physics of Organ Actions. Pykett.org.uk
7. Landry, Simon P and Champoux, François. *Musicians react faster and are better multisensory integrators* (Brain and Cognition, Elsevier inc. 111 (2017) pp 156-162) http:dx.doi.org/10.1016/j.bandc.2016.12.001