Measurement of crispness in food products using acoustic-mechanical techniques: a literature review

Sophia Davies

MSci Physics Project - *'Physics of Cooking'*
Léon van Riesen-Haupt, Prof. Peter Török & Dr. Carl Paterson

Department of Physics, Imperial College London

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1 Introduction

There are many interesting research topics in the physics of cooking. Research on crispness has increased over the past years due to rising consumer demand for crisp food products. Mechanical tests (Vincent, 1998; Ross, 1999; Ross and Scanlon, 2004) have failed to produce significant correlation with sensory crispness and are limited by the geometry and composition of the food sample (Saeleaw and Schleining, 2011). Recently, there has been a particular focus on the measurement of crispness using acoustic-mechanical parameters. Studies on crusted food products with a high-moisture core have proved particularly inconclusive. Developing both a better understanding and acoustic-mechanical measure of crispness across all food types is critical to improving the correlation of instrumental measurement with the sensory perception of food texture. This review assesses studies that have contributed to the development thus far; the first part summarizes research on crispness of solid, brittle food products and the second focuses on that of crusted food products with a high-moisture core.

2 Acoustic-mechanical measurements

2.1 *Crispness of solid, brittle food products*

Mohamed et al. (1982) stated that measurement of both mechanical and acoustic properties could better predict sensory crispness than the measurement of either of these parameters alone, and was confirmed using solid, brittle food products by the work of Chaunier et al. (2005), Chen et al. (2005) and Varela et al. (2006). This integrated measurement approach has since become the dominant method used to investigate crispness of food products and underpins the majority of the developments made in acoustic measurement.

2.1.1 *The relationship between acoustic and mechanical parameters*

Chaunier et al. (2005) investigated crispness in cornflakes using a Kramer shear-compression cell, acquiring the mechanical and acoustic data simultaneously using Labview software (Fig. 1). Spectral analysis was performed to produce normalised power spectra in the frequency domain. The correlation of sensory crispness with maximum force ($R^2 = 0.4$) was found to be lower than both that with the average amplitude of acoustic signals and high-amplitude fraction of acoustic signals ($R^2 = 0.63$ and $R^2 = 0.65$ respectively).

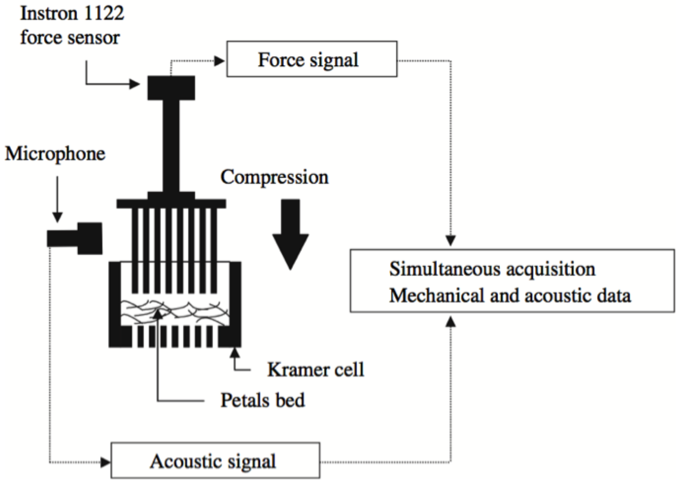

Fig. 1. Instrumental setup of the Kramer shear-compression cell and data acquisition system used by Chaunier et al. (2005).

Chen et al. (2005) investigated crispness in biscuits using a three-point bending device and were the first to analyse mechanical and acoustic data using the Acoustic Envelope Detector (AED) (Fig. 2). The study established the link between mechanical and acoustic properties and is thus intrinsic to all work that has since followed.

It was found that there was an almost one-to-one correspondence between force drops in the force-deformation curve and acoustic signals in the sound pressure level (SPL)-deformation curve (Fig. 3). It was stated that a one-to-one correspondence should not otherwise be expected if such drops in force do not occur over very short time periods (as they did here); the mechanism behind sound dissipation works very differently to that responsible for drops in force in the force-deformation curve. However, it was found that the second derivative of the force-deformation curve linked well with the acoustic signals, indicating the release of energy through the air of fracture events. It was further hypothesised that if the fraction of total dissipated energy in the form of detectable SPL was common to all fracture events, then there should also be a link between the amplitude of the gradient of the force-deformation curve and the amplitude of the acoustic signals. However, this was not evidenced by the data and the reason given for this was related to problems with sound propagation paths in the biscuits.

The work of Varela et al. (2006) on the crispness of almonds, using a compression cylinder and AED (Fig. 4), supported the findings of Chen et al. (2005) through both acoustic-mechanical and microstructural measurement. The work was significant in showing how a chemometric approach to the analysis of acoustic and mechanical data provides a good objective measure of sensory crispness. Furthermore, using a principal component analysis (PCA) (Fig. 5) proved particularly successful in correlating combined sensory, instrumental and compositional measurements. The first PC was found to contain both acoustic and mechanical measures and it was therefore concluded that both of these were required for complete evaluation of sensory crispness. PCA and one/two/three-way analysis of variance are becoming increasingly popular techniques in the analysis of instrumental measurements of sensory food properties.

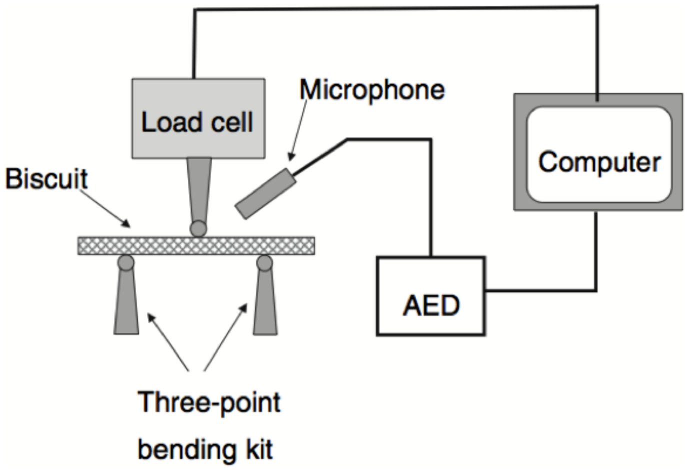

Fig. 2. Instrumental setup of the three-point bending probe and data acquisition system used by Chen et al. (2005).

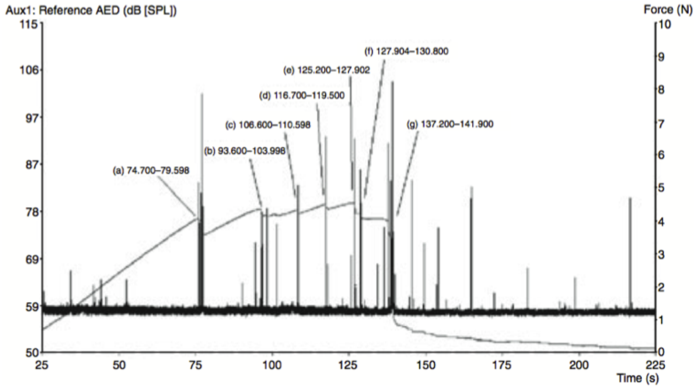

Fig. 3. Typical force- and SPL-deformation curves (in the frequency domain) produced by the three-point bend test of Chen et al. (2005) on a certain brand of biscuit.

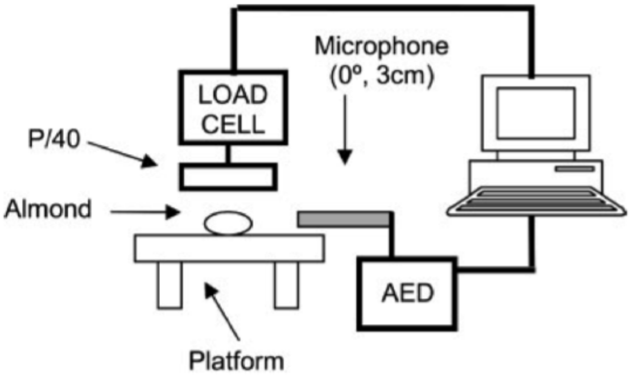

Fig. 4. Instrumental setup of the compression cylinder and data acquisition system used by Varela et al. (2006).

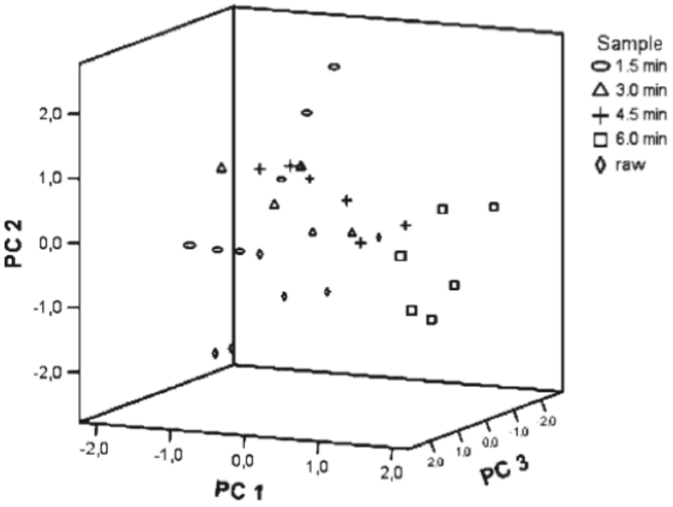

Fig. 5. Example PCA 3-D loading plot of almonds roasted for different amounts of time (Varela et al., 2006).

The measurements of Salvador et al. (2009) on potato chips indicated a good correlation between sensory crispness and the number of force and sound peaks about the point of maximum force. This conclusion is supported by the more recent study of Arimi et al. (2010) of the same parameters in biscuits, where a correlation coefficient exceeding 0.77 was found.

2.1.2 Measurement techniques

One of the major limitations of acoustic-mechanical measurement is the dependence of the results on the method used and type of food tested. The result of this is thorough preliminary testing (Chaunier et al., 2005; Chen et al., 2005; Varela et al., 2006).

Varela et al. (2006) found that different types of compression cause changes in the fracture mechanics and, in turn, changes in the acoustics. Castro-Prada et al. (2007) found the amplitude of the recorded acoustics to depend on the fracture event, available propagation paths and the position of the microphone. Chen et al. (2005) found changes in the acute angle positioning of the microphone to have little to no impact on measurement, agreeing with the statement made by Castro-Prada et al. (2007) that free-field microphones have the least directional dependence of existing models.

However, alterations in the distance from the fracture event were seen to cause more significant changes in measurement. Castro-Prada et al. (2007) discussed how free-field conditions need to be created when using these microphones and that these can be achieved by using an acoustically isolated chamber, which also acts to reduce the signal-to-noise ratio, and positioning the microphone a specific distance (based on its geometry) from the source.

Acoustic artefacts have also been found to have a significant impact on measurements. Castro-Prada et al. (2007) found an interesting contribution from mechanical apparatus. Aluminium probes in both three-point bending and wedge compression devices caused resonance. A Perspex blade was thus used as the preferred probe.

Additionally, the increased use of AED demands careful testing of integration times (Chen et al., 2005). The use of acoustic transducers is also particularly problematic since they are limited to detecting sounds conducted through the air; those conducted by the jawbone have been proven to be particularly important in the perception of sensory crispness (Saeleaw and Schleining, 2011).

2.2 *Crispness of crusted food products with a high-moisture core*

Whilst there are numerous studies in the literature on crispness of solid, brittle food products (Chen et al., 2005; Chaunier et al., 2005; Varela et al., 2006; Castro-Prada et al., 2007; Salvador et al., 2009), there remains very little conclusive work pertaining to that of crusted food products with a high-moisture core (Antonova et al., 2003).

2.2.1 *Individual analysis of the crust*

Studies have mostly focused on the crusts of battered or breadcrumb-coated food products, analysing these by separating them from the core either before (Fan et al., 1997; Mohamed et al., 1998) or after the frying process (Baixauli et al., 2003; Ling et al., 1998; Maskat and Kerr, 2002; Salvador et al., 2005). Ross and Scanlon (2004) investigated the fracture mechanics of fried potato crust using the former crust-core separation method for tensile tests. However, such analysis methods are limited in that they account solely for the outermost layer of the composite food product (Varela et al., 2008). Indeed the deformation of the exterior definitely depends on the mechanics of the crust, but the mechanics of the core also has a contribution (Varela et al., 2008). The contribution of each layer to such behaviours remains difficult to quantify (Luyten et al., 2004).

To reduce the complication of the mechanics of the core, where both shear and compression forces are present (Varela et al., 2006), fracturing data is often only analysed up until the point at which the crust is penetrated (Sanz et al., 2007). Van Loon (2005) performed mechanical tests on French fries, analysing the region in the force-deformation curve up until penetration of the crust, using the method of Visser et al. (2008). This method counts the number of peaks above a set threshold. The number of peaks during fracture was found to correlate with sensory crispness. Sanz et al. (2007) were the first to measure crispness of French fries using an acoustic-mechanical analysis. The method of Visser et al. (2008) was used to measure the number of peaks in the region up until the crust penetration point in both the force- and SPL-time curves as a function of the size of the peak (threshold). Preliminary tests indicated a suitable minimum threshold value above which the contribution of noise to the measured number of peaks was reduced. It was found that multiplying the number of peaks by each threshold 'enhanced clarity', particularly for higher thresholds. There was a greater distinction between samples with different pre-frying times across all thresholds for the acoustic data than there was for the mechanical data, indicating acoustic measurements were more sensitive to differences in fracture behaviour. The study also investigated the relationship between moisture levels and crispness, considering both the moisture content of the entire French fry and that solely of the crust. It was concluded that differences in crispness due to different pre-frying times could only be understood in terms the latter.

2.2.2 *Analysis of the entire crust-core structure*

There are some studies in the literature that analyse properties of the entire crust-core structure of breaded fried chicken nuggets. Antonova et al. (2003) investigated the correlation between instrumental parameters and sensory crispness of such nuggets. Measurements of both ultrasonic and mechanical properties were made using 250-kHz dry-coupling ultrasonic transducers and a Kramer shear-compression cell, respectively. Ultrasonic velocity was found to have a higher correlation ($R^2 = 0.83$) with sensory crispness than mechanical peak force ($R^2 = 0.64$). Sahin et al. (2005) and Firdevs Dogan et al. (2005) both analysed the texture of nuggets using a conical probe to find the maximum peak force required for 25% penetration, the former study proving to be particularly inconclusive. Varela et al. (2008) suggest that the limitation of such methods is that the mechanical parameters they measure relate to hardness and toughness, which are not direct measurements of crispness in crusted food products.

Varela et al. (2008) developed a new method to assess the crispness of crusted food products with a high-moisture core. The study involved acoustic-mechanical analysis of chicken nuggets that were cooked in various different ways, combining parameters derived from the force-deformation curves of the entire sample with those of the simultaneously emitted sound. Preliminary mechanical tests (including penetration, compression and cutting) identified that cutting with a Perspex blade was the best method to achieve good discrimination and reproducibility of force curves and sound peaks. The AED used in previous studies (Chen et al., 2005; Varela et al., 2006) recorded the SPL. Both force-deformation and SPL-deformation curves were plotted together using synchronised signals for real-time analysis.

Fig. 6 shows the texture profiles for the four different cooking methods studied. Force curves DF and CO had similar texture profiles and comprised two distinct regions. The first was an increase in force with very few significant drops in force, corresponding to deformation of the sample without any cutting. The second was an increase in the number of significant drops in force, corresponding to fracture caused by cutting. The pick-up in force preceding this marked the termination of the propagation of this fracture by heterogeneities and the beginning of further deformation. Both the jaggedness and high number of force drops in these two profiles was indicative of crispness.

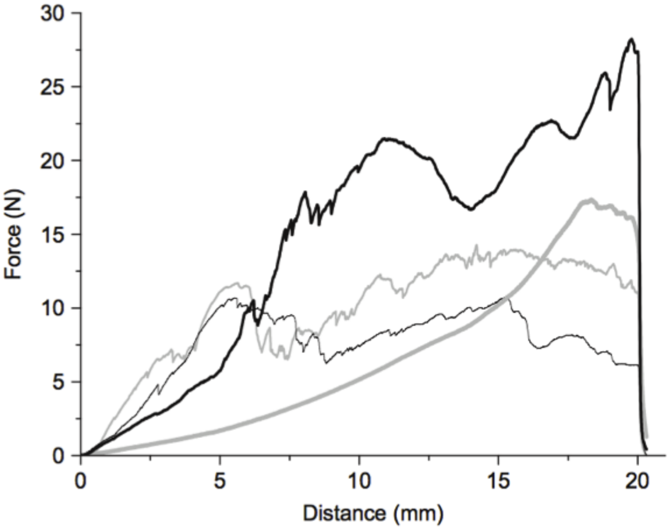

Fig. 6. Force-deformation curves of a certain sample of chicken nuggets subject to four different cooking methods: conventional oven (CO) (thin black line), microwave oven and susceptor (MW + S) (thick black line), deep-frying (DF) (thin grey line), and microwave oven (MW) (thick grey line) (Varela et al., 2008).

Fig. 7 shows an overlay of both the force-deformation and SPL-deformation curves for the DF method. As expected, peaks in SPL accompanied all significant drops in force. However, caution was given to the assumption that such drops in force arise solely from fractures in the crust. It was highlighted that many of these could also arise from other heterogeneities in either the crust-core interface (e.g. air spaces) or in the core itself (e.g. bubbles). It was noted that some small drops in force did not appear to correspond to any peaks in SPL and it was suggested that these could indicate deformations of the core producing no sound and thus no contribution to sensory crispness. Discussion on the non-stringent requirement for one-to-one correlation of the peaks was also given based on the distinction between the origin of sound and force signals given by Chen et al. (2005).

A suggested extension was quantification of the correlation of the peaks by measuring the fraction of applied energy released as detectable sound. Reference was made to the findings of Chen et al. (2005) concerning the time correlation of fracture events with energy dissipation. However, calculation of the second derivative of the force-deformation curves did not improve correlation. The reason given for this (and the challenges this problem poses in general) was explained using the work of Luyten et al. (2003) on how the contribution of each form of deformation energy (stored elastic energy, dissipated fracture/other energy) to the released energy depends on the material. Luyten et al. (2003) showed that dissipative energy processes other than fracturing have an impact on the available energy for fracture and sound events. Chen et al. (2005) also predicted that one-to-one correlation would unlikely be found for soft food materials. Using these studies, it was suggested that a significant amount of the energy applied to the food product was likely stored elastically in the soft core.

Analysis of mechanical parameters included both the area under the force-deformation curve and the total number of force peaks. It was found that the latter better discriminated between the crispness of the samples, agreeing with earlier studies done on solid, brittle foods (Chen et al., 2005; Varela et al., 2006; Vincent, 1998). Similar analysis was performed for the acoustic parameters and the number of sound peaks was again found to be the best discriminator between the crispness of the samples. Particular emphasis was placed on the fact that this preferred parameter related directly to crispness since it measures only the fracture events that emit sound.

Complementing the work of Varela et al. (2008), Primo-Martín et al. (2008*b*) used an acoustic-mechanical method to study the fracture behaviour of bread crust and what affect certain ingredients had on this. The jagged structure of the force-deformation curve seen to arise from the fracture events was attributed to the gradual breakdown of the crusts cellular structure. The distinction between the texture profile of crusted foods and solid, brittle ones was exemplified using a separate mechanical analysis of a baked crispy roll with the crumb removed. As expected, the jaggedness was common to both samples, but there was a continuous decline in force after the first force maximum for the crispy roll. Therefore, this study supported conclusions that the soft core of crusted foods allows for further deformation and fracture events after the first major fracture event.

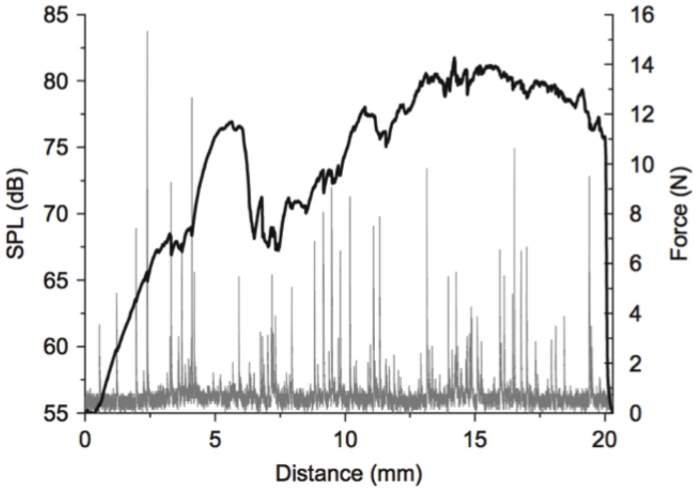

Fig. 7. Force- (black line) and SPL-deformation (grey line) curves for a certain sample of chicken nuggets cooked using the DF method (Varela et al., 2008).

Primo-Martín et al. (2008*b*) added to the acoustic analysis of Varela et al. (2008) by recognising a reduction in acoustic emission once passing the first force maximum. A suggested reason for this, other than just a deeper penetration into the crumb, was that fracturing involves the opening of pre-existing cracks on the lateral part of the bread that form on cooling. This could perhaps suggest that the fracture mechanics of crusted foods with high-moisture cores is inherently different to that of solid, brittle foods and depends strongly on the cooling process.

In a further study of the fracture behaviour of bread crust, Primo-Martín et al. (2008*a*) focused on the effect of air and vacuum cooling for different storage times. A greater number of large fracture events were measured for the vacuum cooling process. Force and sound events were found to decrease with increasing storage time, correlating to an increase in the measured moisture content of the crust. An extension of this work would be to focus on why this increased moisture content reduces the number of measured fracture events.

3 Conclusion

The majority of acoustic-mechanical research on crispness is focused on only one of what is an amalgamation of complex behaviours in food products. The literature pertaining to measurement in crusted food products with a high-moisture core is particularly inconclusive and research into possible differences in the underlying physical mechanisms is required. Indeed current studies have already suggested a number of important extensions.

Conclusively, development of both the understanding and instrumental measure of crispness across all food types will significantly improve the correlation of instrumental measurement with sensory perception of food texture.

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