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Experimental Analysis of Impacts with Large Elastic Deformation

Part 1 : Linear Motion

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Short title : Experimental Analysis of Impacts

Abstract

A measurement system is presented which uses a small number of sensors to capture relevant information by a limited number of measurements during a high speed impact between two lightweight bodies. Two laser Doppler vibrometers and a piezo-electric accelerometer are arranged to capture data from which the variation of deformations, velocities and forces over time during an impact can be determined. The golf club - ball impact is chosen as an example. Large elastic deformations are measured on the golf ball during the impact and these can be related to the variation of the impact force over time. This information leads to greater understanding of the relationship between two impacting bodies and can be used in the validation of analysis by techniques such as finite element modelling.

1. Introduction

This paper describes a successful experimental procedure to obtain physical measurements during a high speed, short duration impact between two lightweight bodies, in which large elastic deformation occurs. The approach taken is to make maximum use of a small number of sensors and to infer important data from this limited number of measurements. This approach is more practically viable than using many sensors, which would incur unacceptable expense and demand considerable data acquisition capability. The particular situation under investigation is the impact between the golf club and golf ball but the conclusions drawn are of general applicability. Impacts in sport are characterised by large elastic deformation of the equipment and, in this respect, differ from more widely studied impacts involving gross

irrecoverable deformation, generally of automotive or military equipment. The techniques described are, however, suited to these applications also.

A sensing arrangement is presented in which a piezo-electric accelerometer is attached to one of the impacting bodies and complementary measurements are made remotely on the second body using laser Doppler vibrometers positioned at the impact site. The piezo-electric accelerometer is suited to the study of high speed impacts where a colliding body moves in a manner such that signal retrieval by electrical connection is possible. Laser Doppler vibrometers are more relevant to impacts where a colliding body is either projected a substantial distance away from the impact or damage would be inflicted on traditional contacting sensors during the post-impact motion. In the golf club - ball impact it is appropriate to use one sensing method of each type. A method of extracting relevant information from the data captured by these instruments during impact is described, hence the variation of deformations, velocities and forces over time during the impact can all be determined. Information of this nature leads to greater understanding of the relationship between the two bodies in time and space and provides validating data for techniques such as finite element modelling. This paper, which will consider only linear motion, is the first of a series which will also describe rotational motions and wave propagation.

2. Sensing equipment details

The accelerometer used is a robust transducer weighing 2 grams, with a resonant frequency of 50kHz and shock limit of 250kms^{-2}. It was mounted on the back of the golf club head, a stainless steel shell of mass 200 grams, and thus measured the

acceleration of the body in the direction of impact during the collision. The relatively low mass of the accelerometer causes minimum disturbance to the system under investigation and its large frequency range and high shock limit are ideally suited to impact measurement. Acceleration was chosen as the most convenient descriptor of the club head motion to facilitate investigation of disturbances on top of a fairly high steady velocity. The variation of the mean force experienced by the body during impact can be estimated from these acceleration measurements.

The laser Doppler vibrometer is a non-contacting velocity transducer which is generally employed in vibration measurement systems where the target object is hot, light or rotating. Its non-contact operation makes the technique well suited to measurements of motions on impact (Birch & Jones, 1990) but application of the technique to the evaluation of dynamic deformation of a colliding body has not been previously reported. The effectiveness of the laser Doppler vibrometer in this role is limited to target velocity and acceleration ranges of $\pm15\text{ms}^{-1}$ and $\pm2\times10^{6}\text{ms}^{-2}$ respectively. Remote measurements of the quality achieved in this work, on a lightweight impacted body subsequently projected from the impact site are, however, unobtainable by other means. The vibrometer focuses a small beam of coherent light on the target, collecting the returning light in direct backscatter. According to the Doppler principle, the frequency of the light returning from the target is shifted in proportion to the component of the target velocity which lies along the axis of the incident laser beam. By electronically tracking the frequency shift, the vibrometer can measure this component of the target velocity.

The laser vibrometer's usefulness in impact measurements can be maximised by intelligent alignment of the probe laser beam. Relevant components of target velocity can be selected and the vibrometer aligned to measure only these. For example, on targets which are both translating and rotating, both motion types will contribute to the measured velocity. In this study, the translational velocities are of greatest interest and sensitivity to rotation is minimised by aligning the laser beam to pass through the centre of rotation of the target or parallel to the rotation axis, in which case the rotational velocity in the direction of the incident laser beam is zero. The measurement is not affected by the shape of the target object, as the vibrometer is sensitive only to the velocity of the illuminated particles on the surface (Rothberg & Halliwell, 1995). An important consideration for all non-contact measurements on moving bodies, however, is the changing position of the measurement point as the target is displaced from its original position. These matters will be discussed at appropriate points in this paper.

A reliable trigger signal is essential for simultaneous data capture from both sensors. In this study a trigger was created by making the club head and ball behave as an electrical switch, closing a circuit in the instant contact is made. The technique is obviously suited only to electrically conducting surfaces, so a region of the ball surface was made conductive by pressing a copper foil strip of thickness $50\mu m$ into the ball cover material during manufacture. The copper foil adopted the dimple pattern of the ball and its presence did not affect the launch velocity or spin rate. The switch also provided a measurement of the impact duration, as the start and end of the contact were clearly defined. The interval between start points of signals from the electrical switch and the accelerometer was established, allowing the accelerometer signal to be used as the

trigger in later measurements, thus simplifying the measurement system. All measurements were stored on a digital oscilloscope at a sample rate of 4MHz.

3. Golf club - ball impact

Modern designs of hollow golf club head undergo very small elastic deformations, whilst golf balls experience gross elastic deformation and recovery during impact. The velocities involved in the impact approach 60ms^{-1} and the event is of approximately 450µs duration. This difficult measurement situation has been addressed in previous studies by the use of stroboscopic video (Scheie, 1990 : Gobush, 1994). The mechanical insight which can be obtained from high speed video analysis is limited by the image resolution available at high frame rates. The highest currently available frame rates are of the order of 40,000 frames per second, which provides only 18 frames of the impact. The smallest resolvable deformation of a golf ball on images produced at high frame rates is approximately 0.75mm, which is insufficient to analyse the golf ball during the impact event effectively. The acceleration and velocity data obtained from the instruments described in the introduction to this paper are used to determine club head and ball translations as well as the pattern of gross deformation and recovery of the ball during the impact in significantly greater detail than previously possible. Further analysis demonstrates how the force experienced by the club head during impact is determined by the pattern of ball deformation and recovery.

The golf club is believed to behave as a free body during impact (Cochran & Stobbs, 1968). It is therefore preferable to swing the golf club during tests, as any setup in which a fixed club head is impacted by a moving ball will not reflect realistic impact

conditions. However, the potential difficulties of measuring small deformations on bodies travelling with a velocity of 45-60ms^{-1} are considerable. These difficulties explain the current lack of accurate data relating to mechanical behaviour during impact and the tendency for previous investigations to rely on measurement of golf ball launch characteristics to test the properties of golf clubs (Olsavsky, 1994). Such measurements generally rely on several video images taken in the first few milliseconds of ball motion (i.e. immediately after but not during the impact), whereas the measurements presented in this paper enable study of the impact itself.

The impact of a golf club head with a stationary golf ball can be accurately and repeatably recreated using a hydraulic robot golfer. The 'Iron Byron' machine is capable of delivering the club head at up to 45ms^{-1} with a positional accuracy of $\pm$ 1mm. In addition to attaining a forward velocity of up to 60ms^{-1} during the impact, the ball is observed to undergo significant deformation in the contact region. Other, smaller extremes of deformation are recorded diametrically opposite the contact site and also perpendicular to the direction of the intended line of flight. These deformations will be termed the contact approach, X_{CON}, the free approach, X_{FREE}, and the lateral deformation, Z_L, respectively, and are defined in Figure 1, which shows a cross-section of the ball through its equator. Additionally, the golf club - ball collision is an example of an oblique impact. Backspin is generated on the ball due to the 10.5° loft of the golf club face and misalignment of the impact can produce sidespin of the ball. Although video images show no appreciable spin of the ball whilst in contact with the club, the generation of backspin and sidespin velocity components during the impact must be

recognised. These are defined as rotation about the Z-axis and about the normal to the X,Z plane respectively.

3.1 Measurement of the lateral deformation, Z_L, during impact

A laser vibrometer, aligned in the X,Z plane of Figure 1, perpendicular to the intended ball flight path and focused to a point on the surface, records the lateral deformation velocity of the ball, $\dot{Z}_L$, during the impact. Figure 2 is a plan view of the arrangement. There is no sensitivity to either whole body forward motion, approach deformation or backspin of the ball at launch as these motions do not have a velocity component in the direction of the laser beam. Sidespin of the ball does not affect the measurement initially but may become important when the forward ball motion means the point of incidence of the laser beam is no longer through the centre of rotation. However, the amount of sidespin on a correctly aligned impact was confirmed as negligible following stroboscopic video experiments taken simultaneously.

The ball moves forward a distance of approximately 10mm during the impact, causing the point on the surface of the ball illuminated by the stationary laser to move towards the club head during the period of measurement. Although the vibrometer is insensitive to the slightly increased optical path length to the ball, it is recognised that the lateral deformation velocity is not recorded at the same point on the ball throughout the impact. This becomes particularly important in the later stages of each measurement, when the ball's forward displacement is largest. Further work will be directed towards accommodating this effect, which is apparent with any non-contact measurement.

A velocity measurement taken by the vibrometer during an impact in which the club struck a ball at 35.5ms^{-1} is shown in Figure 3. It can be seen that in the first half of the impact the lateral deformation velocity of the ball, $\dot{Z}_L$, is towards the vibrometer. In the second half of the impact, the ball attempts to recover its original shape and the measured velocity is negative. Deformation velocities of the order of 10ms^{-1} are recorded. Integration of the $\dot{Z}_L$ measurement over the contact time allows the corresponding lateral deformation, Z_L, to be calculated. This is shown in Figure 4. The maximum lateral deformation is shown as 0.67mm for the case of impact at an initial club head speed of 35.5ms^{-1}. The effect of the ball forward movement relative to the laser probe beam will be to underestimate marginally the extent of the lateral deformation recovery. Further, the figure shows how at the end of the impact the ball 'over recovers' to a lateral dimension less than that of a static ball. This is the start of a heavily damped oscillation which is a feature of the initial ball motion. This lateral deformation data is important evidence in the validation of finite element models.

3.2 Measurement of the forward ball velocity during impact

In the previous section, it was shown how a laser vibrometer aligned perpendicular to the intended flight path of the ball could be used to measure the component of ball velocity in that direction. However, a vibrometer pointed at the ball approximately parallel to the intended flight path cannot be used to measure the forward velocity in this application because the velocity limit of the instrument is only 15ms^{-1}. During impact the ball attains a forward velocity in the region of 60ms^{-1} and the measurement would exceed the instrument range well before the end of the impact. Tests showed that the minimum angle from the X-axis at which the vibrometer could be placed in order to

stay within its velocity range whilst measuring a component of the forward velocity was 75°. In this configuration the maximum rate of change of velocity is also within the range of the laser vibrometer's frequency tracker.

By positioning the vibrometer at this angle, a measurement is made which contains components of velocity due to whole body forward motion, lateral deformation and longitudinal deformation of the ball. The component of velocity due to lateral deformation in this measurement is determined by making a simultaneous measurement at the same point on the ball using a second vibrometer aligned perpendicular to the X-axis, V_{90}. Figure 5 shows measurements conducted at point D on the ball. In this location the laser beam from the vibrometer positioned 75° from the X-axis is aligned to pass through the centre of the ball, making the V_{90} measurement sensitive to sidespin throughout the impact and the V_α measurement insensitive to sidespin only initially. This is acceptable since the amount of sidespin is negligible in a correctly aligned impact. Arranging the laser beams in the X,Z plane and through the equator of the ball makes both measurements insensitive to backspin. The forward velocity, $V_{O,D}$, can be calculated as follows :

$$V_{O,D} = \frac{V_\alpha - V_{90}\sin\alpha}{\cos\alpha}$$

(1)

Example measurements are shown in Figure 6 and the calculated forward velocity from rest is shown in Figure 7. A peak forward velocity of 52ms^{-1} is obtained, which is in agreement with the velocity calculated from a stroboscopic video motion analysis system. The video system has a measurement tolerance of 5%. The largest source of

error in the vibrometer measurement is thought to be the potential misalignment of the vibrometer positioned 75° from the X-axis, where a 0.5° vibrometer misalignment would result in a 3% error in the calculated forward velocity. The peak acceleration of the ball is seen from Figure 7 to be of the order of 30,000g.

A greater insight into the club-ball relationship during impact can be obtained by changing the location of the laser measurement point on the ball. The arrangement of two vibrometers used earlier is again employed to derive the forward velocity, $V_{O,i}$, at five locations on the ball in the X,Z plane, i=A,B,C,D,E. The forward velocity measurements obtained from each of the locations B, D and E are plotted in Figure 8 and together show how the initiation of forward velocity through the ball progresses from the contact site to the free side. The data in Figure 8 also reveals how measurements taken at point B and, therefore, also point A are high estimates of forward velocity in the early stages of the impact. The forward velocity associated with the longitudinal approach deformation is the cause of a high V_α measurement in this case. Also, the measurement from point E is initially the lowest estimate of forward velocity. This suggests an initially smaller value of V_α due to deformation of the ball and is thus evidence for the existence of an initially negative free approach, X_{FREE}. The negative free approach exists due to the presence of the lateral deformation. However, at approximately 200μs into the impact the lateral deformation begins to recover, as shown earlier in Figure 4. At the same time, the forward velocity measurement from point E becomes an overestimate with respect to that from point D, suggesting the presence of an additional positive forward velocity component and the recovery of X_{FREE}. The timing of the change from velocity underestimate to overestimate at point E

is further evidence for the stage in the impact where the ball begins to recover its undeformed shape and cause a significant increase in the force exerted on the club head. Towards the end of the impact, the measurement initially taken at point E will be approximately at point D due to forward movement of the ball. This will cause an underestimate of the X_{FREE} recovery. The existence of approach deformation in the forward velocity measurements at points A,B & E suggests that $V_{O,C}$ and $V_{O,D}$ are the most reliable estimates of the true ball forward velocity. $V_{O,D}$ is presented in Figure 7.

3.3 Measurement of the contact approach, X_{CON}, during impact

The contact approach, X_{CON}, is defined in Figure 1 and can be obtained by integrating the relative velocity of the two bodies over the contact time, as shown :

$$X_{CON}(t) = \int_0^t \left(V_{club,1} + \int_0^t a_{club} dt - V_{O,D} \right) dt$$

$$(2)$$

Thus, the forward velocity of the ball obtained in the previous section is used along with the club head acceleration measurement, a_{club}, and the club head impact velocity measurement, $V_{club,1}$, to obtain X_{CON} by integration over time, t. With the piezo-electric accelerometer mounted on the back of the club head, it is not possible to determine the forces acting on the club face during impact as the club head motion is a combination of rigid body motion and some small deformation. Measurements on the club face during impact are difficult to achieve and may reveal additional information relating to the deformation of the face. This calculation is, however, unaffected by the small deformations associated with oscillation of the club-ball combination as these become negligible when the accelerometer signal is integrated. The velocity of the club head in the instant before impact , $V_{club,1}$, is recorded using a photocell.

The result of the approach calculated from laser vibrometer measurements at point D is shown dotted in Figure 9. It can be seen that X_{CON} increases up to a point due to deformation of the ball at the impact site. The maximum contact approach is 5.4mm for the case of an initial club head speed of $35.5ms^{-1}$ and this is achieved in a period when the ball moves approximately 1mm forwards. This contact approach calculation, using laser vibrometer measurements at point D, will be larger than the actual value of X_{CON}

because the estimate of X_{CON} from the point D measurement additionally incorporates deformations across the ball in the direction of the X-axis from points A to D. The best estimate of X_{CON} is provided by data from point A but this data is only available for the first 150µs of impact. However, combined data from points A and B produces a close approximation to the true value of X_{CON} and this is shown as a solid line on Figure 9. A maximum value of 4.3mm is calculated. Additionally, the calculation shows recovery of the X_{CON} deformation beyond the original X-axis dimension of the ball in the final stages of contact with the club face.

The pattern of deformation across the ball in the direction of the X-axis during impact can be studied further by comparing the forward displacements calculated at each of the points B to E. The forward displacements X_i are obtained by integration of the forward velocities $V_{O,i}$, where i=B,..,E. Data from point A has been omitted as it is available only for the first 150µs. The relative forward displacements X_{CB}, X_{DC} and X_{ED} are plotted in Figure 10. All three quantities are negative in the first 325µs of the impact due to compressive deformation of the ball. Through the centre section of the ball, this deformation is approximately constant for a significant part of the impact, as seen in the X_{DC} value. In the final 100µs of the impact, X_{DC} exhibits some recovery of the deformation. More significantly, X_{ED} exhibits a greater recovery and becomes positive. Points D and E thus move further apart in the later stages of the impact. This is further evidence for elongation of the ball in the direction of the X-axis.

The deformations identified could not be resolved using a high quality video analysis system with up to 40,500 frames/sec and 256x256 pixel resolution. This longitudinal

deformation data is of key importance in the validation of finite element models of the colliding bodies.

3.4 Estimate of the contact radius, r_{CON}, during impact

A simple estimate of the contact radius, r_{CON}, can be obtained by considering the geometry of the deformed golf ball shown in Figure 1. Assuming the club face to be rigid, the contact radius can be expressed as :

$$r_{CON} = \left(X_{CON}\left(2R - X_{CON}\right)\right)^{\frac{1}{2}}$$

(3)

The variation of X_{CON} over the contact time was calculated in the previous section and R is the radius of the undeformed ball, hence the variation of r_{CON} can be calculated. The maximum contact radius has been calculated as 14.0mm for the case of an initial club head speed of 35.5ms^{-1}. In the second half of the impact, the contact radius declines as shown in Figure 11. Note that although there is a clear over-recovery of the lateral deformation of the ball during the impact, the data suggest that the original shape of the ball at the impact site is recovered only at the very end of the impact. This calculation is important as it gives the spatial variation of the impact force with time.

4. Oscillations occurring during impact

The forward acceleration of the ball, $\dot{V}_{O,C}$, can be obtained by differentiating the forward velocity measured at point C. $\dot{V}_{O,C}$ thus contains components of acceleration due to approach deformation of the ball and forward motion of the ball from rest. Similarly, the lateral deformation measurement, $\dot{Z}_L$, can be differentiated to obtain the lateral

acceleration of the ball, $\ddot{Z}_L$, which is due only to deformation. The accelerations, $\dot{V}_{O,C}$ and $\ddot{Z}_L$ are plotted in Figure 12. In the period of the impact where $0<t<120\mu s$ there is little forward motion of the ball. Thus, the club head deceleration measured in this period is a result of approach and lateral deformation of the ball. After this time, the lateral acceleration of the ball decays. The forward acceleration, however, shows a strong oscillation which can also be seen in the measurement of acceleration taken at the back of the club head in the direction of the X-axis. The club head acceleration measurement, a_{club}, is shown along with the forward acceleration of the ball on a normalised scale in Figure 13. Due to the speed of wave propagation in the synthetic rubber ball, the time taken for the initial impact force to reach the lateral deformation measurement site is approximately $50\mu s$. This is $31\mu s$ longer than the time taken to reach the accelerometer on the back of the club head and thus the $\dot{V}_{O,C}$ trace lags the accelerometer measurement by $31\mu s$. Events occurring simultaneously at the back of the club head and at point C on the ball can therefore be studied together by shifting the a_{club} measurement in time by $31\mu s$, as in Figure 13. This shift is most valid for the period of the impact where $0<t<200\mu s$ as the forward displacement of the whole ball is only of the order of 1mm. In the period $200<t<450\mu s$ the forward displacement of the whole ball increases and the laser vibrometer measurement at point C begins to move toward point B. Thus events occurring simultaneously on the ball and at the back of the club head will appear increasingly out of synchronization in the period $200<t<450\mu s$ in Figure 13.

Both of the accelerations shown in Figure 13 can be considered to have mean and oscillating components. The mean acceleration components, shown dotted, are obtained by smoothing the original data to remove higher frequency information. The mean component of $\dot{V}_{O,C}$ represents the forward acceleration of the ball from rest and the mean component of a_{club} shows a corresponding deceleration. The oscillating component of acceleration in the direction of the X-axis, apparent in ball and club head measurements, is a result of deformation of the club-ball combination. From Figure 13, a relationship between the ball and club head oscillations can be seen. The clarity of the relationship is affected by noise in the $\dot{V}_{O,C}$ trace, which is increased as a result of obtaining $\dot{V}_{O,C}$ by differentiation of a forward velocity measurement. However, it is apparent that local turning points on the $\dot{V}_{O,C}$ and a_{club} traces occur at approximately the same points in time. This is confirmed by consideration of equivalent data for further club-ball impacts. Local maxima in the $\dot{V}_{O,C}$ trace correspond to local minima in a_{club}, showing that when the forward deformation acceleration of the ball is locally a minimum, the forward deformation acceleration of the back of the club head is locally a maximum. The reverse case, in which maximum ball forward deformation acceleration corresponds to minimum forward club head deformation acceleration, can also be deduced from the accelerations shown on Figure 13. This relationship suggests that if oscillations of the club face match those of the ball with which it is in contact, then the club face oscillates out of phase with the back of the hollow club head. The oscillation of the forward deformation of the ball is on top of the gross deformation shown in Figure 9.

The greatest local maximum on the $\dot{V}_{o,c}$ trace occurs at a point 200µs into the impact. This is verified by comparison with Figure 9, where it can be seen that the greatest contact approach, i.e. the point at which the deformation component of ball acceleration in the direction of the X-axis should be greatest, occurs at 200µs into the impact. Beyond this point in the impact the ball recovers and the relationship between the club head and ball is less well defined.

Finally, an estimate of the peak contact force occurring during the impact can be obtained from the mean club head acceleration trace. For a club head of mass 200grams, the maximum mean force is 12kN and occurs 180µs into the impact. Combination of the mean acceleration data in Figure 13 with the contact radius estimate in Figure 11 provides the estimate of the temporal and spatial variation of the force between the club head and ball.

5. Conclusion

A system of measurements has been presented which is suited to the analysis of high-speed, short duration impacts between lightweight bodies in which large elastic deformation occurs. The system uses a small number of sensors arranged to capture relevant information by a limited number of measurements. Using two laser Doppler vibrometers, a piezo-electric accelerometer and a suitable measurement trigger, short duration impact data has been captured from which the variation of deformations, velocities and forces over time during the impact can all be determined. This has been demonstrated by analysis of the golf club-ball impact. The lateral deformation and forward velocity of a golf ball during impact were experimentally measured using a

laser vibrometer. Combining this data with measurements of club head acceleration facilitated estimation of the time histories of :

i)   The force applied by the club to the ball and its relationship to the deformation of the ball.

ii)   The spatial variation of the force applied by the club to the ball across the club face.

ii)   The forward velocity of the ball from rest.

iii)   The deformation of the ball, to a resolution of 0.1mm, in the direction of impact and perpendicular to it.

This wealth of force, velocity and displacement information obtained under difficult measurement conditions from only a small number of sensors is of superior detail and greater mechanical relevance than that obtainable using video techniques. The information is important in the validation of finite element models and provides a foundation for the further study of a variety of impacting bodies.

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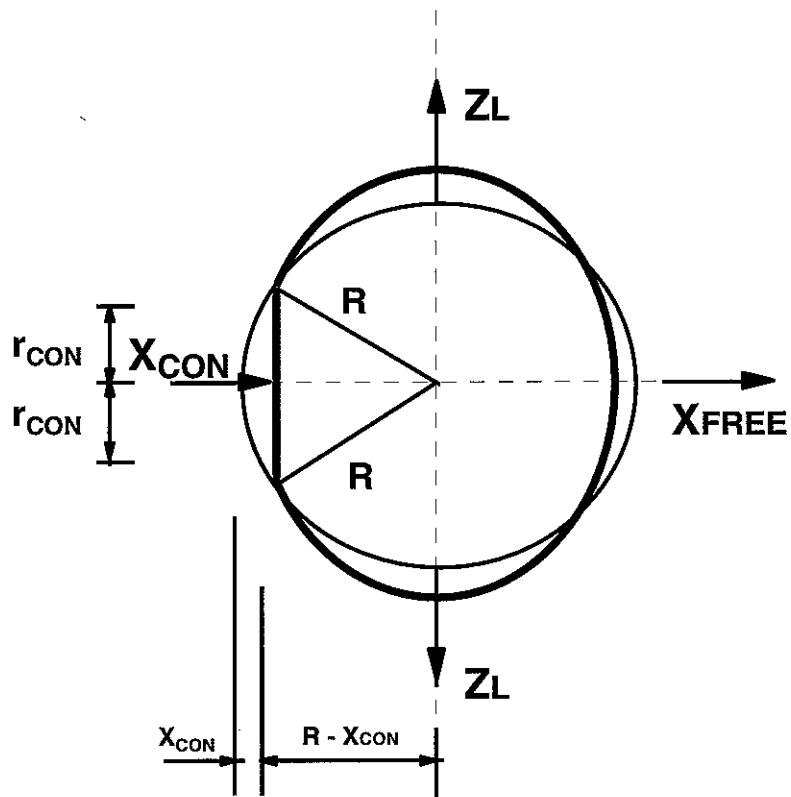
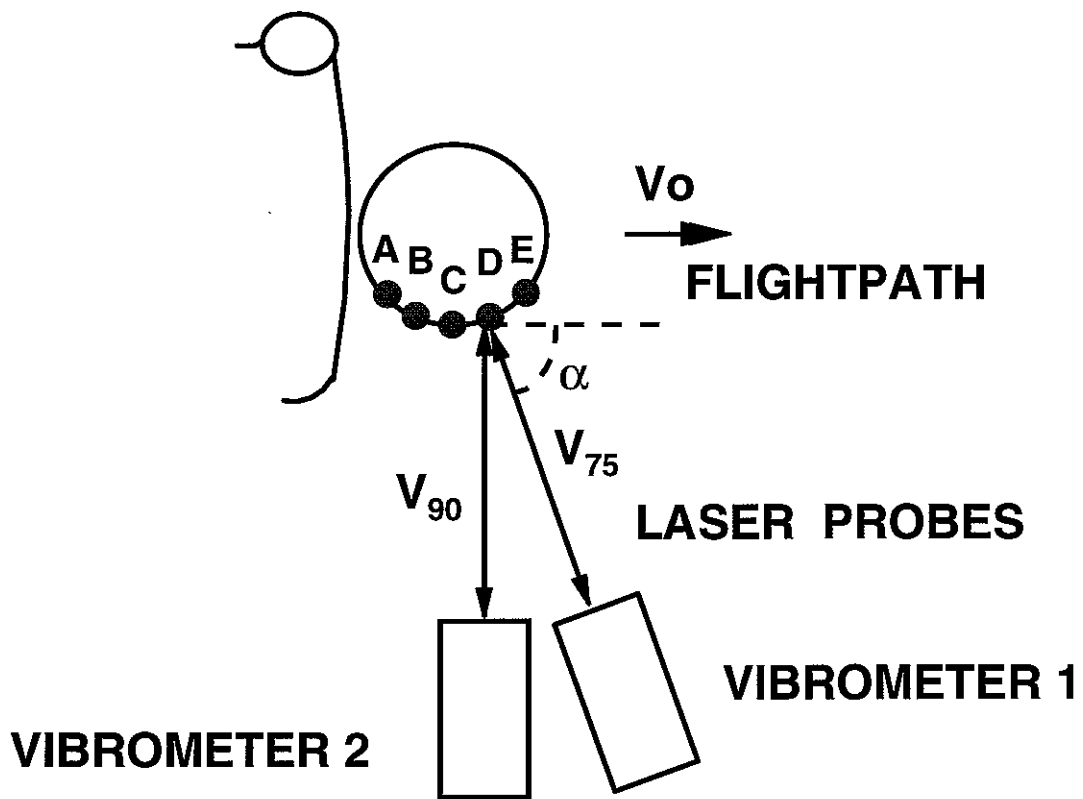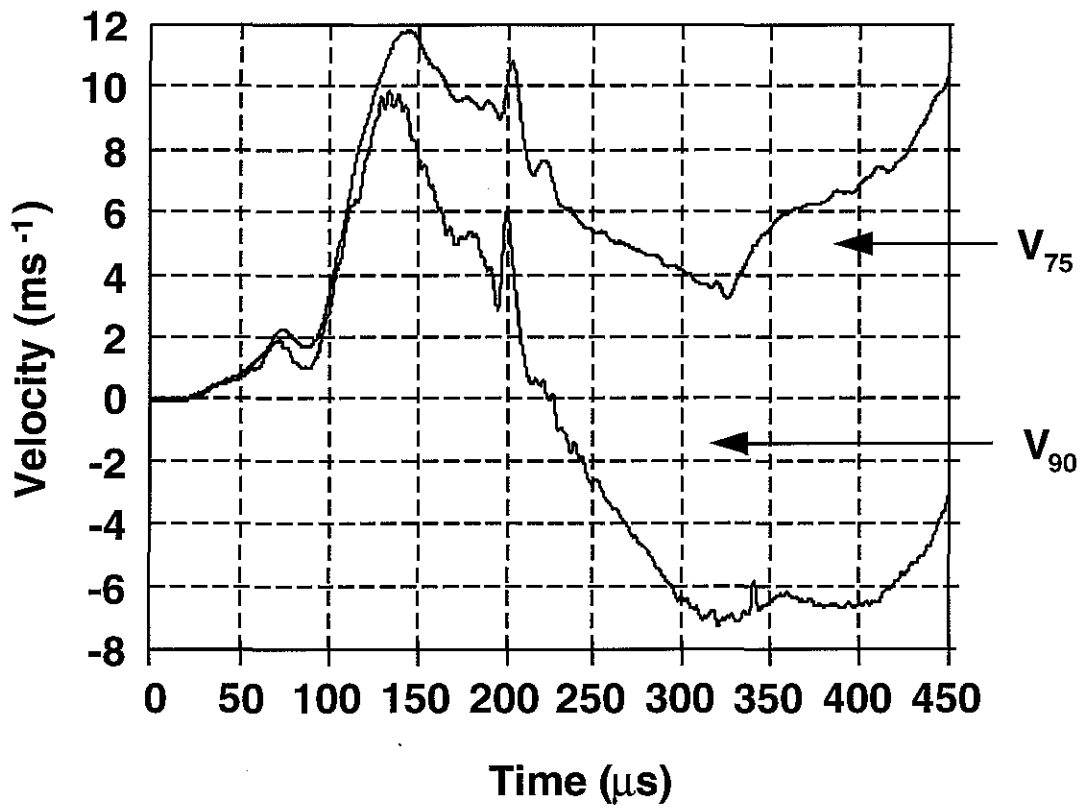Experimental Analysis of Impact with Large Elastic Deformation
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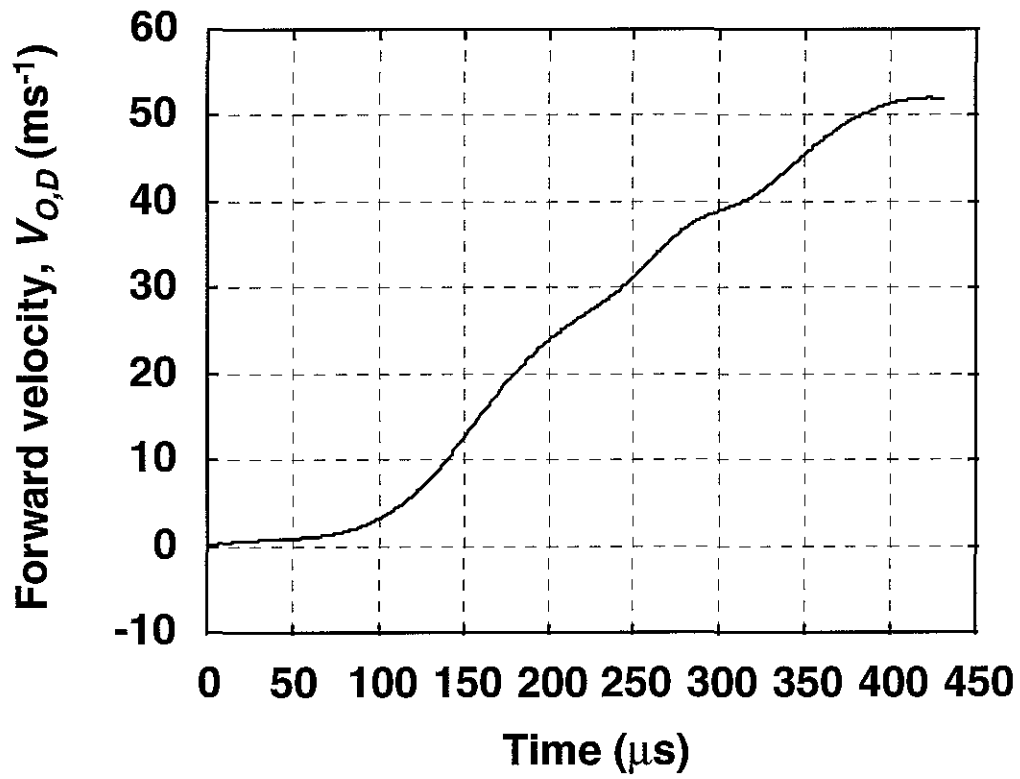Loughborough University
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Figure 1

CLUB HEAD

CLUB PATH

BALL

ACCELEROMETER

FLIGHTPATH

LASER PROBE

VIBROMETER
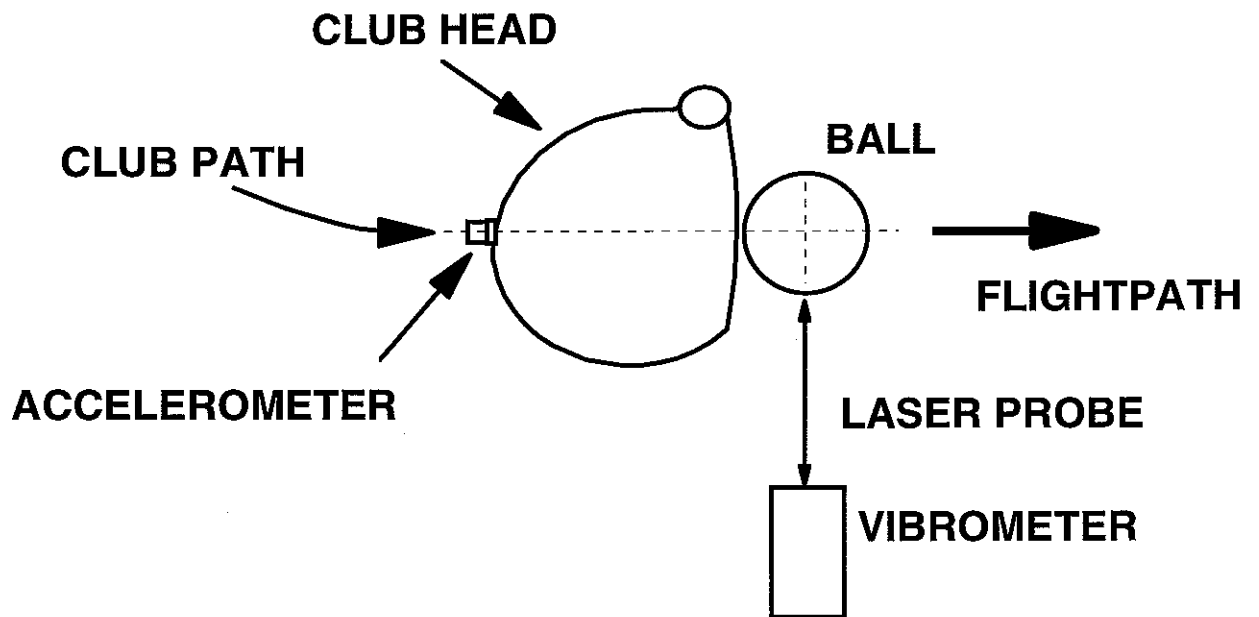
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Figure 2

Experimental Analysis of Impact with Large Elastic Deformation
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Figure 3
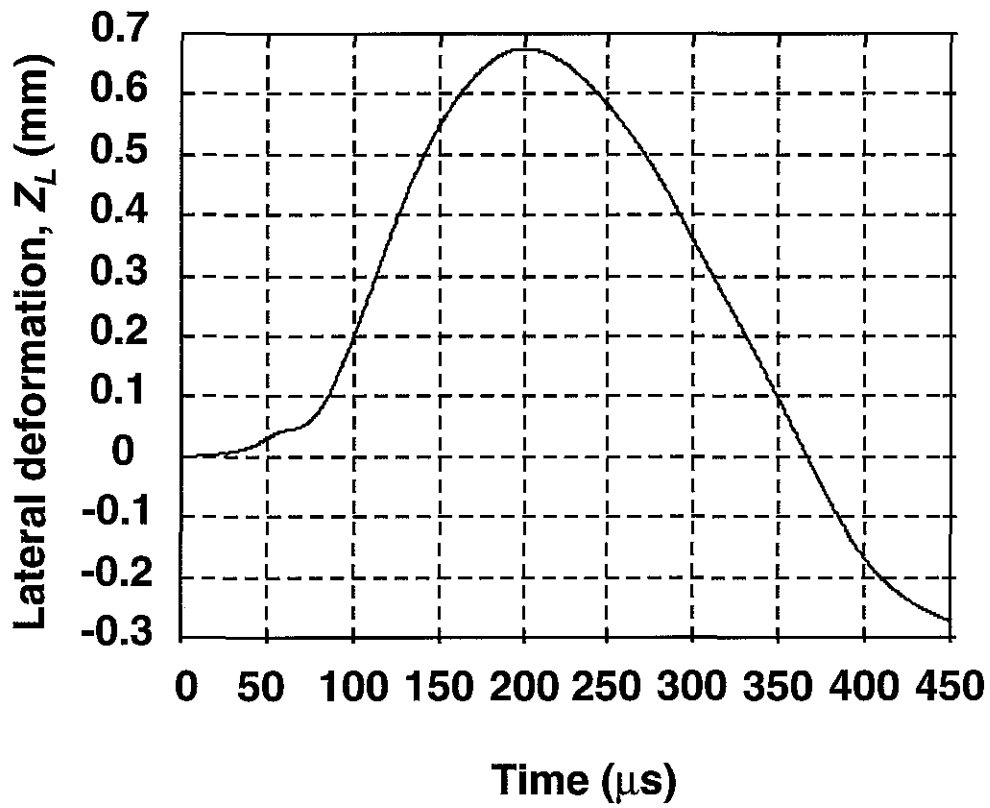
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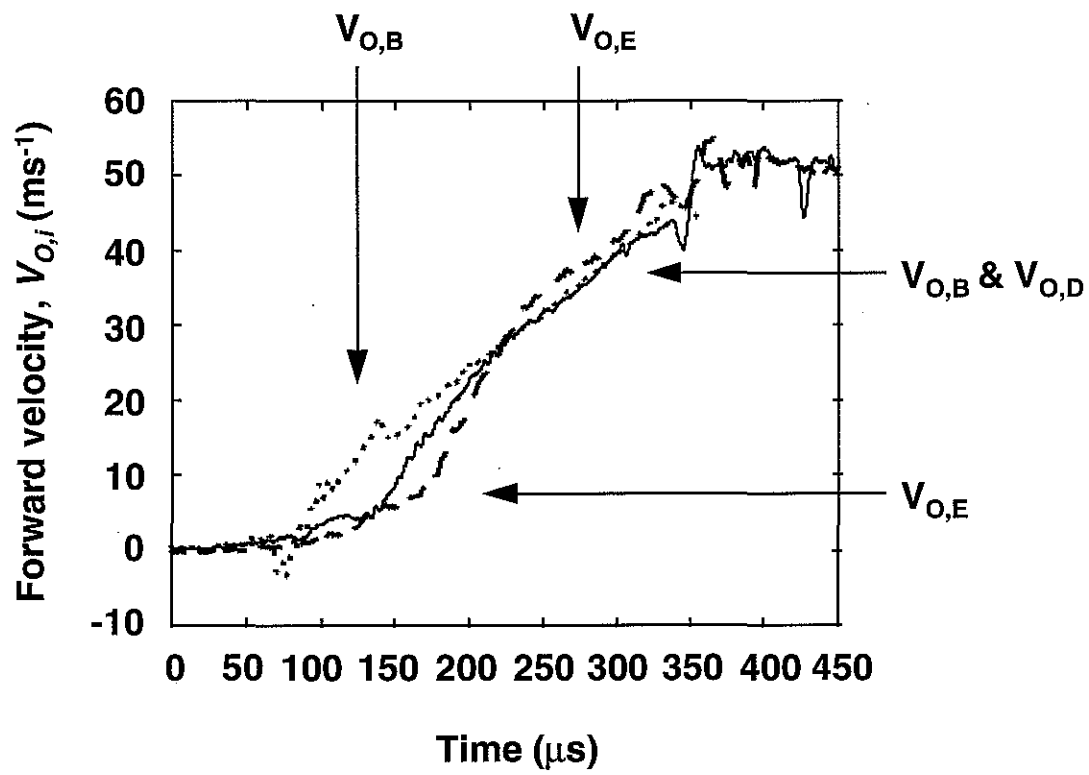Part 1 : Linear Motion
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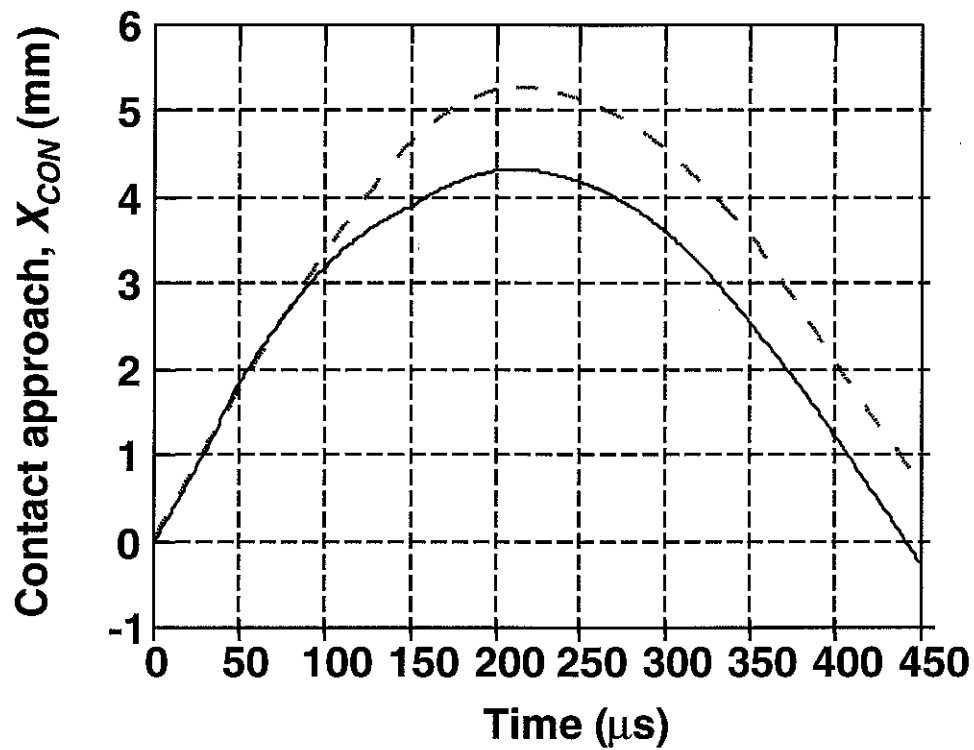Loughborough, Leicestershire, LE11 3TU
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Figure 4

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Figure 5

Figure 6

Experimental Analysis of Impact with Large Elastic Deformation
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Figure 7

Experimental Analysis of Impact with Large Elastic Deformation
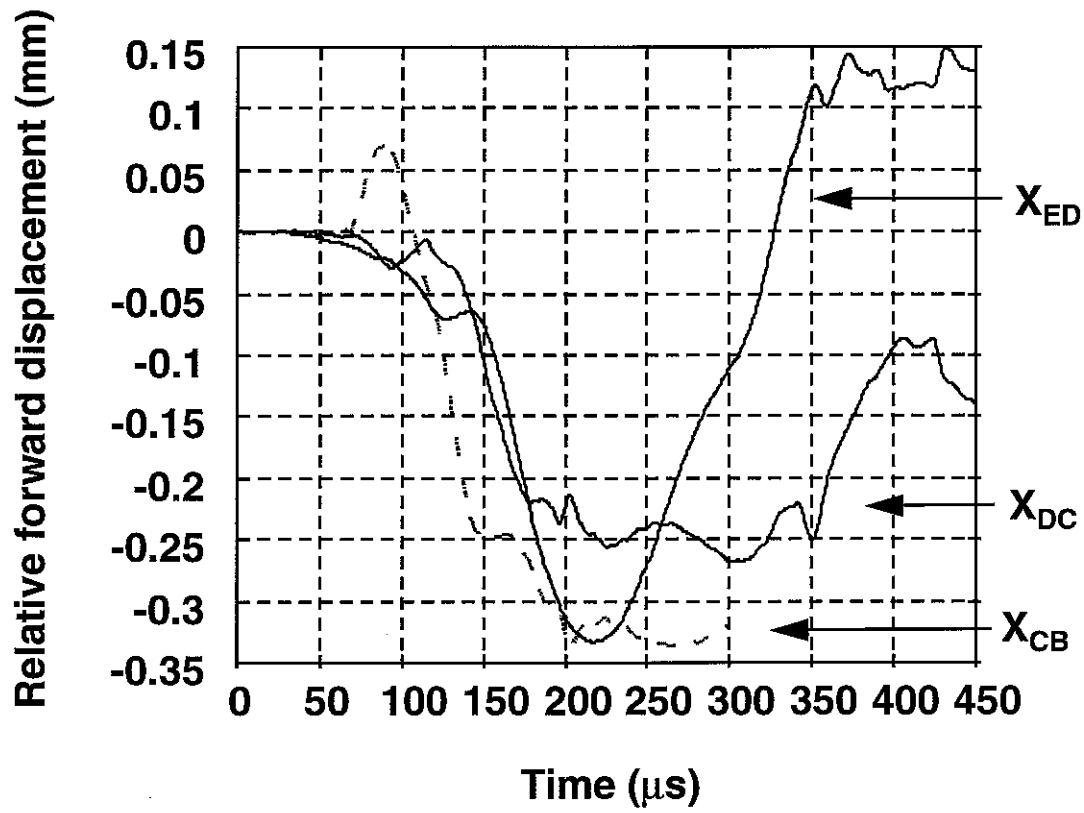Part 1 : Linear Motion
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Figure 8

Experimental Analysis of Impact with Large Elastic Deformation
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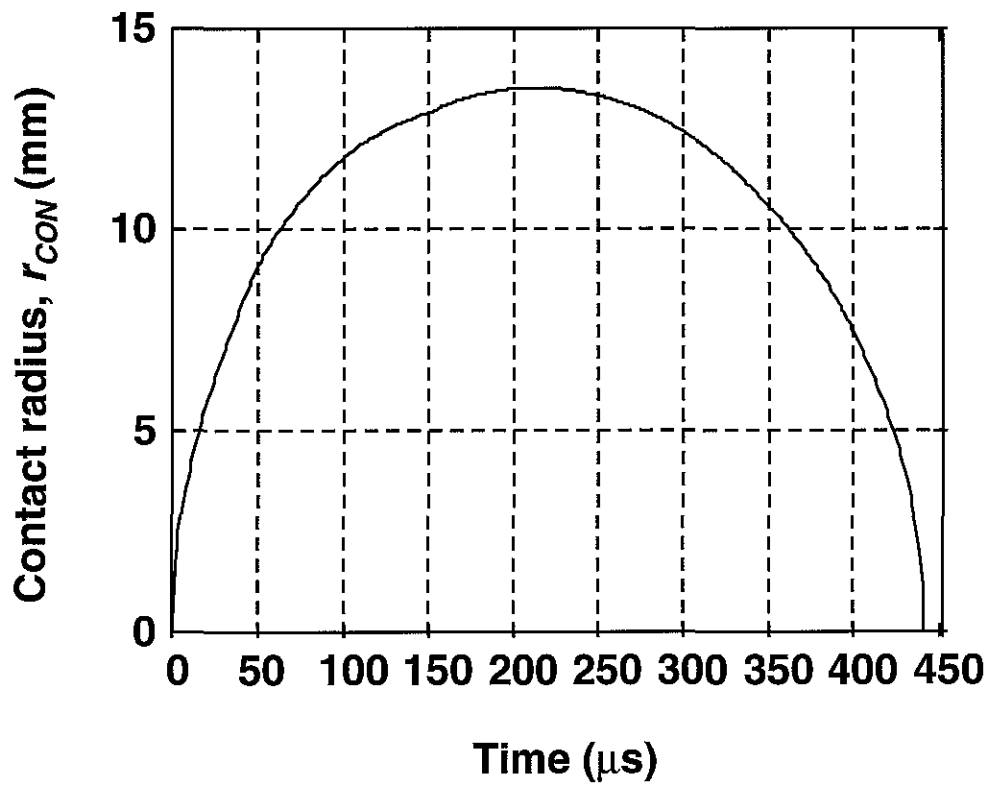Loughborough, Leicestershire, LE11 3TU
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Figure 9

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Part 1 : Linear Motion
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Figure 10

Experimental Analysis of Impact with Large Elastic Deformation
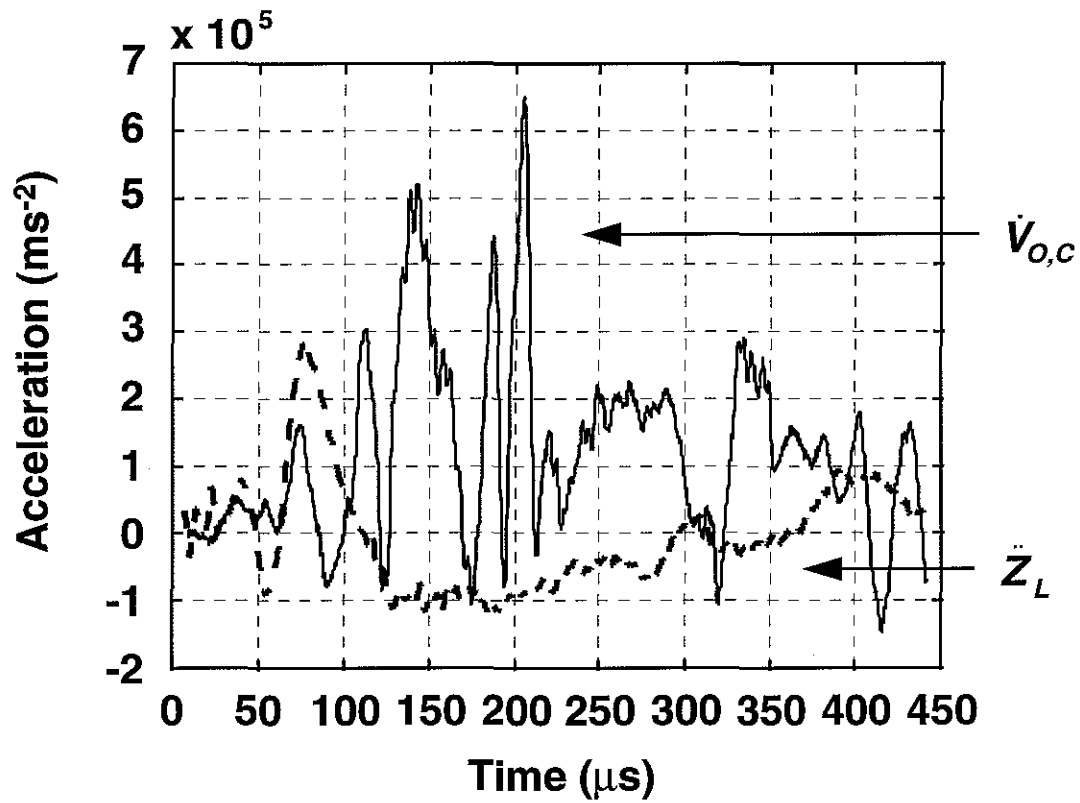Part 1 : Linear Motion
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Figure 11

Experimental Analysis of Impact with Large Elastic Deformation
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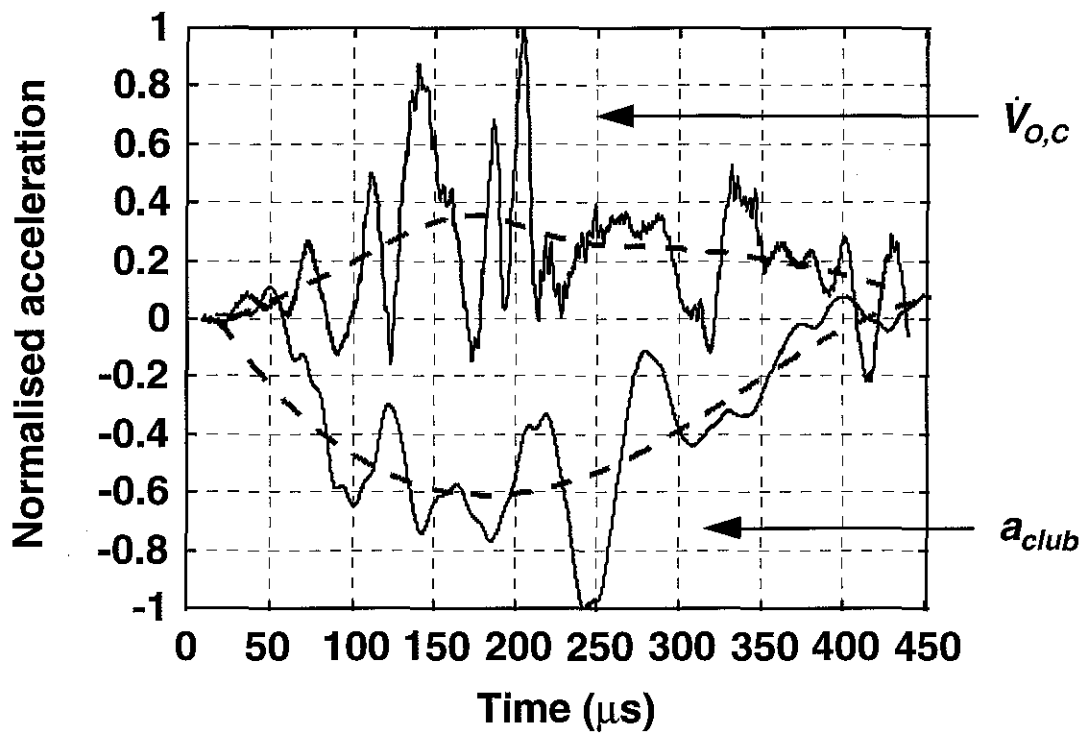Loughborough, Leicestershire, LE11 3TU
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Figure 12

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Figure 13

Figure Captions

Figure 1 - Cross section through the equator of a deformed golf ball, showing measurement axes

Figure 2 - Alignment of the laser vibrometer to measure lateral deformation of the ball

Figure 3 - Lateral deformation velocity, $\dot{Z}_L$

Figure 4 - Lateral deformation, Z_L

Figure 5 - Alignment of two laser vibrometers to deduce ball forward velocity

Figure 6 - Vibrometer measurements at $\alpha=75°$ and $\alpha=90°$

Figure 7 - Calculated forward velocity of the ball, $V_{O,D}$

Figure 8 - Forward velocities calculated from points B,D and E

Figure 9 - Calculated contact approach, X_{CON}

Figure 10 - Relative forward displacements of the ball

Figure 11 - Calculated contact radius, r_{CON}

Figure 12 - Lateral deformation acceleration, $\ddot{Z}_L$, and ball forward acceleration, $\dot{V}_{O,C}$

Figure 13 - Normalised forward accelerations of the ball, $\dot{V}_{O,C}$, and club head, a_{club}

16th April 1996

Editorial Department
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Dear Sir or Madam,

Please find enclosed a paper for submission to the IOP Measurement Science and Technology journal entitled 'Experimental Analysis of Impacts with Large Elastic Deformation, Part 1 : Linear Motion'. I will be pleased to answer any questions which you may have regarding this paper. I can be contacted at the above address or by telephone, on extension 4313, or by e-mailing a.hocknell@lboro.ac.uk.

Yours faithfully

Alan Hocknell