An Assessment of Sensing Technologies to Monitor the Collision of a Baseball and Bat

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TOPICS: baseball, sensors

Abstract: Some of the key parameters that make up the collision of a baseball and a bat include the velocities of both just prior to impact, the horizontal and vertical location of impact, the angle of impact and the geometric and physical properties of the bat and ball. The objective of the batter is to optimize this collision to produce the maximum batted-ball speed at a desired trajectory angle. Through experience, a professional batter uses his senses of hearing, vision and touch to help him develop the swing and timing to create this optimum collision. The location of this optimum impact is commonly referred to as the sweetspot on the bat.

A study was performed to evaluate different types of sensors, such as accelerometers, strain gages and microphones, and to quantify their ability to identify these collision parameters. High-speed motion analysis was used to evaluate the accuracy of the measurements as they relate to location and velocity. Data were collected and were statistically quantified to compare the effectiveness of each technology.

Keywords: baseball, sensors, collision

1- Introduction

A wood baseball bat was instrumented with several different types of sensors. A series of tests was performed using this bat to make an initial assessment of the applicability of these sensors to identify impact location and the swing speed of the bat. The study was as much an investigation of baseball as it was an exercise in simultaneous recording of multiple technologies using a single data acquisition system.

The objective of this initial assessment was to obtain test data, identify problems associated with using these sensors and evaluate methods to process the data. The actual values of strain, acceleration, sound-pressure level were not the main focus, but relative levels were used to draw comparisons of impact locations and swing speed.

A total of five different types of sensors were mounted onto a bat, including four strain gages, four microphones, four piezoelectric accelerometers, a variable capacitance accelerometer and a gyro assembly. The series of tests included stationary bat impacts, noncontact swings and finally swings impacting a ball off a tee. For the stationary impact tests, the bat was supported by a single hand grip approximately 15 cm (6 in.) from the knob. Swinging the bat at the batter's maximum potential would exceed the range of some of the sensors. An effort was made to swing the bat at approximately half-speed.

2- Methodology

2.1 - Instrumented Solid-Ash Bat

A bat's sweetspot is typically located about 15 cm (6 in.) from the end of the barrel of the bat. The solid ash bat used for these tests measured just under 89 cm (34.8 in.) and weighed 0.91 kg (32 oz.) prior to instrumentation. The gyro assembly was mounted on the upper part of the handle facing upward to measure the main axis of rotation. The variable capacitance accelerometer was mounted on the barrel end of the bat. The remaining sensors were grouped into four sets of three sensors and mounted along the bat per the locations specified in Table 1. All distances are referenced from the knob end of the bat.

Sensor	Barrel-End Location 1 (cm)	Barrel-Start Location 2 (cm)	Mid-Bat Location 3 (cm)	Handle Location 4 (cm)
Strain Gage	81.9	64.8	42.2	27.
PE Accelerometer	84.5	66.0	44.5	28.
Microphone	87.9	63.5	42.2	26.

Table 1: Sensor Locations.

The strain gages were installed on the bat using a flexible adhesive over copper tape. The accelerometers and gyro were also attached using a fast curing adhesive, and the variable capacitance accelerometer was further secured with a small wood screw. The microphones were installed along the impact side of the bat, whereas the PE accelerometers and strain gages were bonded to the opposite side. There was concern that the microphone might be affected by the wave propagating along the bat as opposed to the sound pressure transported through the air. To minimize this effect, a viscoelastic damping foam was placed between the microphones and the bat which were then secured using reinforced tape. The speed of sound in ash along the fibre is 4000 m/s (890 mph) and in theory, the impulse travels from the barrel to the handle in 0.21 ms (Cross 1998). However, tests demonstrated that the travel time was significantly longer because the impact on the side of the bat caused an initial propagation across the growth rings which has a speed of sound about ¼ that of the fibre direction (Brinsmead 1889).

2.2 - Sensors

Pre-wired 350-Ohm strain gages, Omega type KFG-3-350-C1-11L3M3R, were used for the testing. The strain gages had a gage factor of 2.1. For the stationary bat tests, the data acquisition settings included a quarter bridge setup, a 5K gain, an excitation of 5V, a 3.3 kHz filter and a sensitivity of 525 mV/Vex. The handle and mid-bat settings were further adjusted to account for increased strain during swinging conditions.

The piezoelectric (PE) accelerometers were Endevco model 2250A-10 which has a frequency range of 2 to 8000 Hz and a maximum acceleration of 500 g. The variable capacitance (VC) accelerometer was Endevco model 7596-30 which has a frequency range of 0 to 800 Hz and a maximum acceleration of 30 g.

The microphones were Panasonic model WM-63PR, Omnidirectional Electret Condenser Microphone Cartridges. Omnidirectional microphones pick up sounds from any direction, because the electronic pick-up is placed in the center of a mesh-covered dome. The microphones were isolated from the ash bat with the objective of only recording the sound wave travelling through the air at 343 m/s (770 mph).

The gyro assembly module had been previously used on rail gun tests and was specifically designed by Draper Lab for high-shock environments. The gyro's support electronics increased the commercial gyro's capabilities to measure rates as fast as 300 deg/s about an axis perpendicular to the module.

2.3 - Data Acquisition System

A Liberty (part no. 269-945083, manufactured by LDS Test and Measurement LCC, Wisconsin, USA) ruggedized DAQ (Data Acquisition) System was used to acquire all accelerometer, gyro, strain-gage and microphone responses. The Liberty DAQ System consisted of the Liberty mainframe, signal conditioning modules, battery module, Perception software and a PC (personal computer) running on a network. The system was supported by a custom aluminium frame. The signal conditioning modules included an eight-channel Bridge Signal Conditioner (BR-8) to acquire the strain gage data, an eight-channel General Purpose Signal Conditioner (GP-8) to acquire the VC accelerometer and a 16-channel General Purpose Signal Conditioner (GP-16) to acquire the gyro module data and an eight-channel ICP Signal Conditioner (ICP-8) to acquire the piezoelectric accelerometer and microphone response data.

The gyro module required an external 5V power supply, and the VC accelerometer was powered with 12V. Depending on the internal settings, the sampling rate was limited from 20 kS/s to 50 kS/s. All of the data collected were stamped using an IRIG (Inter-Range Instrumentation Group) time. The Liberty uses two internal oscillator clocks and was synchronized to a motion analysis system using a video playback feature. A motion analysis system was used to validate the impact location and to measure the bat velocity at impact which could be correlated to the centripetal acceleration measured by the VC accelerometer. The motion analysis system recorded the impacts at 1000 frames/s.

2.4 - General Description of Data Analysis

Sensor response data was captured for the three series of tests and imported into Microsoft Excel files for processing. The data file included time and response values for each sensor. Time values were extracted which corresponded to each sensors first response to the impact of the ball on the bat. Additionally, the time values associated with the peaks of the first microphone responses were also extracted. The time values were plotted against the sensor's location along the bat. A line was curve-fit through the data and the location in which the slope of the line was zero was recorded as the predicted impact location by that type of sensor. This predicted impact location was compared against the actual as measured by the chalk mark and the motion analysis system.

3 - Results

3.1 - Stationary Test

A total of eight impacts were recorded for the stationary tests. Two impacts were recorded at the sweetspot, above the sweetspot, below the sweetspot and near the mid-point of the bat. The variable capacitance accelerometer and gyro assembly data were not recorded during stationary tests as their function was more applicable to determining swing speed. Because the maximum sampling rate for this setup was 20 kS/s, which translates to 0.00005 s/S, the speed of data acquisition did not provide many timestamps between adjacent sensors. Some interpretation of data was required to obtain the initial response of the sensors. The microphone peaks were recorded for only the first pulse because of secondary waves resulting from reflections off the test-room walls. A second time value was also extracted for the microphones which corresponded to the peaks of their first response. Impacts near the handle or end of the bat resulted in some saturated strain-gage data during non-sweetspot impacts.

The data from the stationary tests were manually extracted from the DAQ files and are listed in Table 2.. These data show when the pulse reached each sensor. The accelerometers recorded the first response and the impact was then received by the strain gage and microphones. The timing between impact locations (1-4) was somewhat inconsistent. For example, Run No. 2 was impacted at 72 cm. The pulse first reached accelerometer 2 and accelerometers 1, 3 and 4 with delays of 0.02, 0.06 and 0.13 ms respectively. The microphones responses to the impact occurred from 0.57 to 0.93 ms following the initial measurement and similarly the strain gages responded with a lag of 0.76 to 1.21 ms.

		Strain Gages				Accelerometers				Microphones			
Run No.	Impact Loc.	1	2	3	4	1	2	3	4	1	2	3	4
2	72	-	0.76	0.78	1.21	0.02	0.00	0.06	0.13	0.61	0.57	0.84	0.93
3	80	-	1.20	1.35	1.50	0.02	0.00	0.59	0.69	1.00	1.15	1.50	1.65
5	51	-	0.70	0.75	0.90	0.15	0.05	0.00	0.10	0.79	0.63	0.60	0.72
6	72	0.85	0.80	0.85	0.95	0.00	0.05	0.20	0.27	0.65	0.57	0.95	0.90
7	81	-	0.90	0.95	1.50	0.00	0.07	0.19	0.30	0.55	0.70	0.90	1.00
8	67	-	0.70	0.80	1.15	0.10	0.00	0.11	0.25	0.70	0.60	0.95	0.80
10	67	-	0.75	0.85	1.10	0.15	0.00	0.20	0.25	0.75	0.55	0.90	1.15
11	52	1.60	1.35	0.95	1.00	0.35	0.07	0.00	0.25	0.78	0.60	0.65	0.70

Table 2: Stationary Test Normalized Signal Start Times (ms).

For the stationary bat tests, the bat was impacted with a ball lightly covered with chalk. The chalk left a removable mark on the bat identifying the location of impact. The sensor location was plotted vs. the acquisition time (first response or "start time" for all three sensor types and peak response for the microphone). A 6^{th}-order polynomial fit (Figure 1) was used to determine an estimated impact location. Table 3 summarizes the results and present a first-order accuracy. The PE accelerometers resulted in the best predictor of impact location—being able to predict the impact location within 5 cm (2 in.) and within 2.5 cm (1 in.) 63% and 38% of the time, respectively. The microphones were slightly less accurate with the start time analysis providing better results than the peak-time analysis. The strain gages were the least accurate in estimating impact location partly due to the difficulty in identifying a signal near the end of the barrel.

Perhaps a method that offers better accuracy is a comparison of the peak-value ratios. Table 4 presents the ratios for the PE accelerometers and the microphones. Because of saturation and unidentifiable data on the strain gages, this method was not applicable. A comparison of the peak response levels demonstrated very consistent results for the accelerometers. If a modal analysis were to be performed on the bat, these ratios may offer an excellent method to identify impact. For example, for the two end-of-the-barrel impacts, the ratios of accelerometers 2, 3 and 4 with respect to accelerometer 1, were 2.0, 3.0 and 1.8 respectively for the 80-cm impact and 2.0, 2.8 and 1.4 respectively for the 81-cm impact.

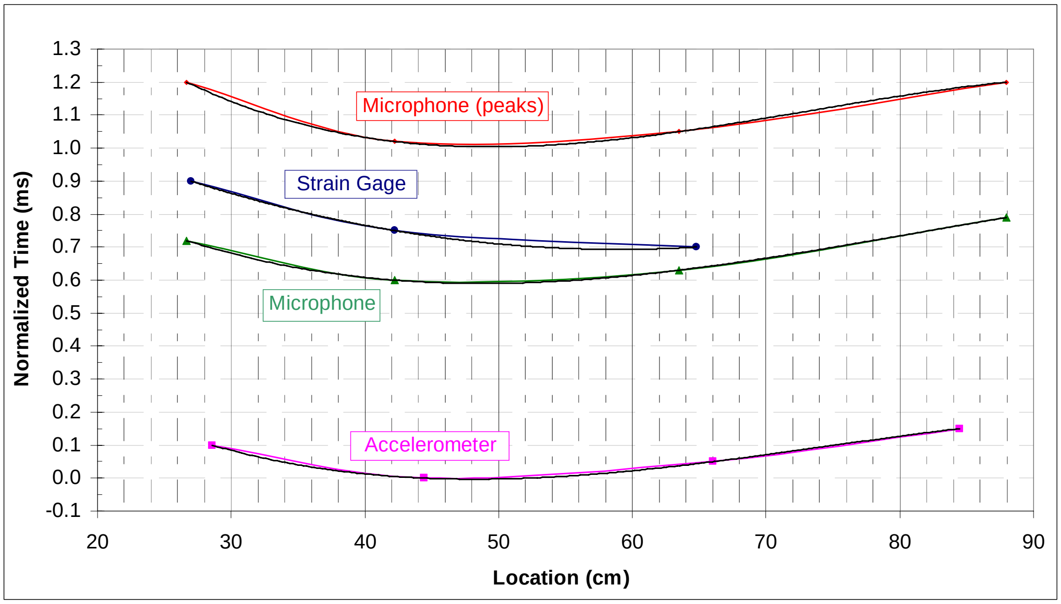

Figure 1: Stationary Run No. 5 Sensor Timestamp vs. Sensor Location.

		Predicted Impact Location (cm)				Error (cm)			
Run No.	Impact Loc.	Strain (start)	Accel (start)	Micro (start)	Micro (peak)	Strain (start)	Accel (start)	Micro (start)	Micro (peak)
2	72		71.5	75.5	72		1	3	0
3	80	82	70.5	81.5		2	10	1	
5	51	59	48	48.5	49.5	8	3	2	1
6	72	75.5	82	75.5	75	4	10	4	3
7	81	54		91	69	27		10	12
8	67	57	67	75	78.5	10	0	8	11
10	67	61	70	71	71.5	6	3	4	4
11	52	38	51	62	71	14	1	10	19
			Average Error (cm)			10	4	5	7
			% Predicted within 5 cm			25	63	63	50
			% Predicted within 2.5 cm			13	38	25	25

Table 3: Stationary Test Results Summary (Time Data).

		Accel Amplitude Ratio			Micro Amplitude Ratio		
Run No	Impact Location	1 to 2	1 to 3	1 to 4	1 to 2	1 to 3	1 to 4
3	80	2.0	3.0	1.8	2.4	-6.3	-1.9
7	81	2.0	2.8	1.4	2.5	-16.8	-34.7
2	72	1.8	2.1	2.6	2.2	14.9	-13.1
6	72	1.9	2.8	2.9	2.2	8.1	4.6
8	67	1.5	1.2	0.9	-0.2	-0.9	2.7
10	67	1.5	1.3	1.2	1.3	6.3	3.5
5	51	0.8	0.4	0.4	-1.8	-5.6	-2.7
11	52	0.7	0.4	0.4	-1.3	-3.0	-2.4

Table 4: Stationary Test Results Summary (Peak Data).

3.2 - Swing and Tee-Hitting Tests

With the bat fully instrumented, several practice swings were taken to set the gains on the transducers and to capture swing data without impact. Figure 2 shows a photo of the tee-hitting test set-up. The photograph shows the instrumented bat, the ball on a tee (construction cone), the power supply, DAQ system the locations 1 through 4 and sensor wiring harness.

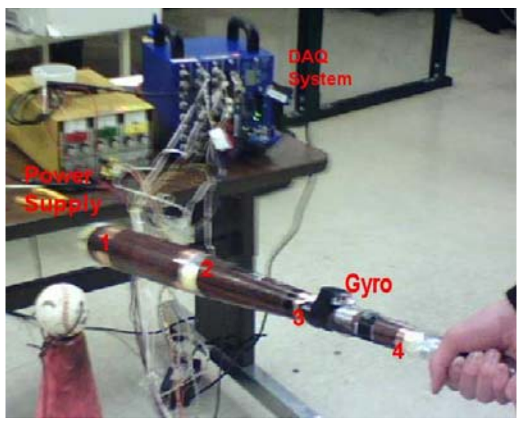

Figure 2: Tee-Hitting Test Set-Up.

Figure 3a plots non-impact swing data of the gyro module and VC accelerometer. The response levels were normalized and are dimensionless. The accelerometer provided essentially a noise-free response, where the gyro had considerable noise. A polynomial trend line through the gyro data aided in interpreting the results.

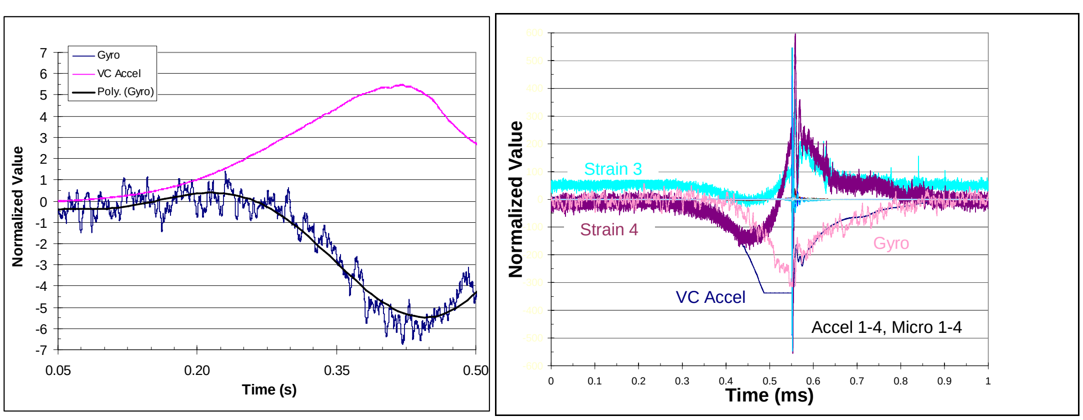

Figure 3: a) Non-Impact Swing, b) Impact off Tee.

Several impacts were recorded during Tee-Hitting including two sweetspot and two non-sweetspot impacts, and those data are presented here. Figure 3b plots each of the sensor types during a sweetspot impact. The data were rescaled to help in visualizing the results. The plots indicate some gyro and VC accelerometer offset after impact. The VC accelerometer also saturated at maximum swing speed. The strain on the handle indicates the gages in compression during the start of the swing with the gages 3 and 4 switching to tension prior to impact. If these gages are correlated for the length of the bat, it is possible to determine if the "whip effect" was maximized upon impact (i.e. the small strains at the location opposite the impact point switch from compression to tension precisely at impact).

Based on the accelerometer data for the four impacts, the average pulse speed along the bat was 2100 m/s (6900 ft/s) which falls between the published numbers for along the fibre and across the growth rings. To improve the curve-fitting method used to calculate impact location, an imaginary (extrapolated) accelerometer was assumed to be 18 cm (7 in.) beyond Accel 1, just off the end of the barrel. It was assumed that this accelerometer start time occurred at a time equivalent to that of Accel 1 plus 18 cm (7 in.) divided by 2100 m/s. Table 5 lists the accelerometer response data which were slightly less accurate than the stationary bat results. Impact number 5 was first recorded by Accel 2 followed by Accels 1,3 and 4 with lag times of 0.03, 0.21 and 0.32, respectively. Impact 5 predicted an impact location 2 cm different from that recorded by the motion analysis system. Additional testing with the bat rotated 90 degrees and an off-center impact demonstrated that the accelerometers and strain gages could be used to determine the severity of the eccentric impact.

Impact No.	Impact Location (cm)	Extrapolated Accel (ms)	Accel 1 (ms)	Accel 2 (ms)	Accel 3 (ms)	Accel 4 (ms)	Predicted Impact Loc. (cm)	Error (cm)
-	-	102 cm	84 cm	66 cm	44 cm	29 cm	-	-
5	74	0.12	0.03	0.00	0.21	0.32	72	2
6	51	0.22	0.13	0.00	0.07	0.15	61	10
7	84	0.09	0.00	0.06	0.12	0.18	87	3
8	74	0.09	0.00	0.03	0.12	0.20	81	7
					Average Error (cm)			6
					% Impact Predictions within 5 cm			50
					% Impact Predictions within 2.5 cm			25

Table 5: Tee-Hitting Test Results Summary (Normalized Accel Start Time Data).

7- Conclusions

All five sensors provided useful data when analyzing the swing and impact. There were issues with limitations which caused voltage saturation in some cases. The VC accelerometer, gyro module and strain gages provided information on the swing although the strain gages and gyro had considerable noise. The accelerometers and microphones were the best at determining impact location with the most consistent and most promising method of data interpolation being accelerometer peak *G* ratios as compared to modal analysis results.

8- References

[B1] Brinsmead, E., The History of the Piano, Simpkin Marshall & Co., 1889.

[C1] Cross, R., The Sweetspot of a Baseball Bat, American Association of Physics Teachers, 1998.

9- Acknowledgement

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