Effect of Airbag Deployment Phases on Tactile Occupant Detection Sensor

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***Abstract*—An airbag is a crucial passive safety system that protects an occupant in the event of severe vehicle collisions. Its restraint effect can be controlled only when the occupant's contact data with the airbag is available. A new capacitive tactile sensor is developed and installed on the airbag surface to provide the occupant's first contact time, contact area and position on the airbag. Based on this feedback, the airbag pressure can be controlled. An airbag deployment is associated with different phases from trigger to full deployment. Before detecting the occupant, it is important to know the effect of these phases on the sensor. In this paper, the phase effects of dynamic airbag deployment on the contact sensor during the simplified static deployment tests are analyzed and discussed. Time-to-first-gas, unfolding of the textile, inflation, and cable capacitance effects are the key points brought to discussion. The results reveal, no effects of time-to-first-gas and inflation on the contact sensor. While the unfolding and cable capacitance have significant effects on the sensor which should be accounted for the occupant detection algorithm.**

***Keywords*—Accidents, Airbag deployment, Capacitive tactile sensor, Passive safety, Restraint effect, Vehicle crash testing**

I. INTRODUCTION

An airbag deploys in 30 to 50 milliseconds during severe vehicle collisions and restrains the occupant from the life-threatening forces of the crash [1], [2]. The airbags deploy commonly in one stage, while the dual-stage airbags are employed for extended protection time [3]. Both are partially controllable. An alternative is controlling the opening time of the vent holes. An adaptive tether tightens and closes the vent holes, thereby provides longer protection time [4]. Furthermore, controlling the restraint effect requires the occupant data feedback. For this purpose, an occupant detection sensor is required. There are several attempts in this direction to detect the occupant and adjust the restraint effect accordingly [5], [6]. A parallel plate fixed capacitive sensor is one such attempt. It is installed outside the airbag in the cockpit and it measures the occupant position and speed [5]. Another approach is, installing a distance measuring sensor inside the vehicle compartment. The combination of this sensor with the occupant weight sensor gives the position of the occupant [6]. Both the sensors are not an integral part of the airbag and fail to explain what happens after contact with the airbag. Therefore there is a call to develop a sensor which is an integral element of the airbag. In the present research, a new tactile sensor is developed which comprises a conductive woven fabric and a conductive thread which are knitted on the airbag. The sensor is an integral part of the airbag and follows the dynamics of the deployment. This paper deals only with the effects of deployment phases on the developed sensor, it does not discuss sensor design and development or the occupant detection method.

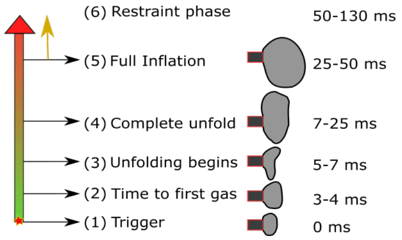

Fig. 1. Airbag deployment phases

An airbag deployment has many phases before it restrains the occupant. From [7], [8] and several static deployment tests at CARISSMA (Technische Hochschule Ingolstadt), different contact sensor performance influencing phases are identified. Fig. 1 shows the major deployment phases considered for the investigation in this work. Each phase affects the sensor because there is a likelihood of change in dielectric value or the capacitance. Before the occupant detection and classification, it is essential to account for these effects in detail. Based on the results from this research, the deviations and errors are incorporated in the occupant detection method and the restraint effect control algorithm. The airbag deploys within

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milliseconds. In this work time is divided into six phases: Trigger, First gas, Unfolding start, Complete unfold, Full inflation, and Restraint phase (Fig. 1). This eases the time window for the study. Numerous static deployment tests are performed with the sensor. Finally, pendulum impact tests at low impact velocity (3.41 m/s) are carried out to analyze these phases in more broadband scenarios in scaled-down impacts.

II. CAPACITANCE THEORY

A capacitor is a device that is composed of two electrically charged plates separated by a dielectric material. Fig. 2 (a) shows a basic capacitor [9], [10]. The construction of the capacitor can be tweaked and converted to a sensor. The sensor consists of a conducting layer below a dielectric layer. When a finger or any charged object comes in contact with the sensor, it creates another virtually grounded plate and completes the capacitor. This works on the principle of self-capacitance [9] - [11]. Fig. 2 (b) shows the schematic of a sensor.

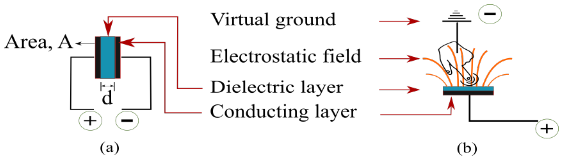

Fig. 2. Capacitive sensor

The sensor follows the same theory of a capacitor. From the fundamentals, the equation of the capacitance is given by (1) [9], [10].

$$C = \frac{\varepsilon_0 \varepsilon_r A}{d} \tag{1}$$

Where C is the capacitance. ε_0 and ε_r are permittivity of free space and dielectric material respectively. A is the area of plates and d is the separation distance.

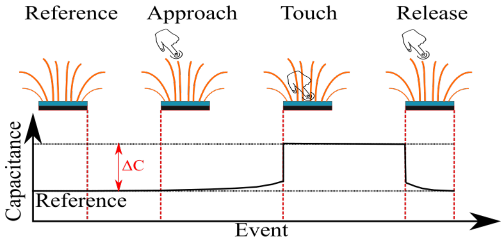

Fig. 3. Touch detection

Fig. 3 shows the principle of touch detection and sensor's capacitance change. A sensor has a reference capacitance value which has to be calibrated in the beginning. After the calibration, a threshold value can be set to detect the touch. During the touch, the capacitance value changes by ΔC. A suitable threshold should be used to ensure the touch and avoid false recognition due to phase effects [11]. Equation (2) gives the voltage across the capacitor.

$$V_c = V_s(1 - e^{-t/RC}) \tag{2}$$

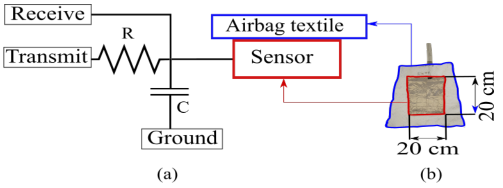

Fig. 4. Circuit schematic

Taking natural logarithm and rearranging (2), equation (3) is obtained.

$$C = \frac{-t}{Rln(1 - \frac{V_c}{V_s})} \tag{3}$$

Where V_c is the voltage across the capacitor and V_s is the supply voltage. t is the time elapsed after the supply and R is the resistor value. C is the capacitance across the sensor.

A pulsating signal of a known voltage is supplied for a known time (milliseconds). If there is a change in the capacitance, the voltage across capacitor also changes. This change can be measured. Equation (3) gives the capacitance value. Change in capacitance can be measured and converted to any suitable parameter. In this work, it is converted to voltage.

Fig. 4 shows the simple circuit diagram of the sensor and its application on the surface of the airbag. It consists of a resistor connected to the sensor. A suitable capacitor can be connected between the ground and the resistor to stabilize the sensor. The output voltage change is measured across the sensor in the transient state [10], [12]. Arduino Uno R3 development board is used to implement the circuit. A digital pulse is supplied to the sensor and analog voltage change is measured from the sensor.

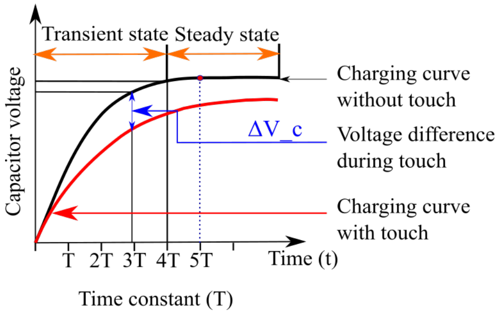

Fig. 5. Capacitor charging

Fig. 5 shows the voltage curves of the capacitor with and without touch. When there is a touch, capacitance increases by ΔC and voltage reduces by ΔV. Further, various other capacitance values influence the sensor. These are parasitic capacitance, traces, touch, air gap, and the ground separation. The capacitance at the receiver end will be the equivalent of these values which is given by (4) [12].

$$C_{eq} = (C_p + C_t + C_{to} + C_a + C_{gs}) \tag{4}$$

III. TEST BENCH AND TESTING

A. Test Bench

Fig. 6 illustrates a low impact velocity pendulum test bench designed and constructed to address the needs of the different tests. The choice of the pendulum is because of the flexibility to change the velocity and energy. The test bench consists of two components, airbag mounting fixture and a pendulum structure. An airbag module is utilized for static deployment. It is mounted on a wall-mounted rigid fixture. The fixture is designed to restrict airbag rigid body motion. All the mounting conditions are maintained without change for all the tests discussed in this paper. The airbag is inflated with a central air supply unit kept at 10 bar absolute pressure. The pendulum consists of a swinging arm of length 2.03 m and a steel-head form of mass 6.81 kg. Two high-speed cameras at 200 fps are used to capture the test videos.

During the impact tests, a conducting thread is connected to the pendulum structure and the human body to simulate a real human touch. Human body has a capacitance of 100 to 300 pF [9].

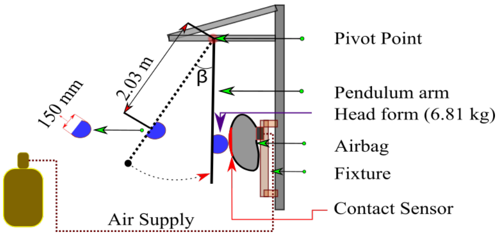

Fig. 6. Test bench

B. Test Matrix

A test matrix is designed to test the sensor from various aspects shown in Fig. 1. Table I describes the test matrix. Initially, the airbag is folded and stowed in the fixture and reference values are measured. This test is followed by the time-to-first-gas experiments, where the airbag pressure is increased until it reaches the threshold of unfolding. Unfolding beginning and complete unfold are combined and tested as a single process. Following these investigations, impact tests are carried out with an impact velocity of 3.41 m/s (45° swing angle) and 34 kPa relative airbag pressure. These tests simulate scaled-down crash situations from trigger to restraint phase. Each test is repeated three times to ensure the repeatability.

TABLE I
TEST MATRIX

Number	***Test condition***
1	Folded airbag reference value
2	Time-to-first-gas
3	Unfolding with non grounded cable
4	Unfolding with grounded cable
5	Impact test with non grounded cable

IV. RESULTS AND DISCUSSION

The reference value of the sensor is crucial to detect the touch. Voltage drop is calculated from this reference value. Initially, reference value tests of the sensor folded with the airbag are carried out without any contact (Number 1 from Table I). Fig. 7 visualizes the first reference value test. There is a data acquisition lag with Arduino and CoolTerm data acquisition software. The lag is 1 second and is repeatable in all the tests. This lag is accounted for the data processing in all further tests discussed here and has no relevance to the results. The plot has raw data, trigger, and the sensor averaged value. The raw data has been averaged with 30 points moving average. Different sample size for the average is considered and 30 is found to be the best with all event and signal content retention. The averaged sensor reference value is 4.1 V. Fig. 8 shows the plot of the average value of three successive reproducible tests.

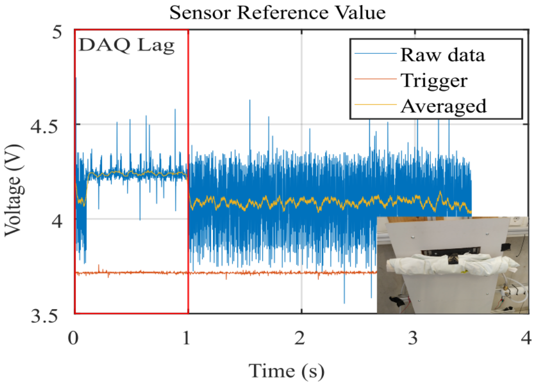

Fig. 7. Sensor reference value

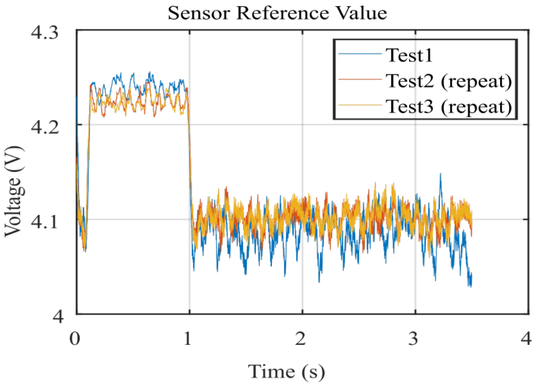

Fig. 8. Three tests sensor reference value

After the reference tests, the effect of time-to-first-gas is studied (Number 2 from Table I and Fig. 1). In this experiment, the airbag pressure is increased until the airbag just starts to unfold. The airbag is not fully deployed in this test. Fig. 9 shows the effect of pressure on the sensor. The pressure is released into the airbag at 2.34 s and stopped at 7.35 s. A mechanical trigger is used to identify the start and stop of the pressure. In this time window, increasing the pressure does not affect the sensor. This effect can be excluded from the restraint effect control algorithm.

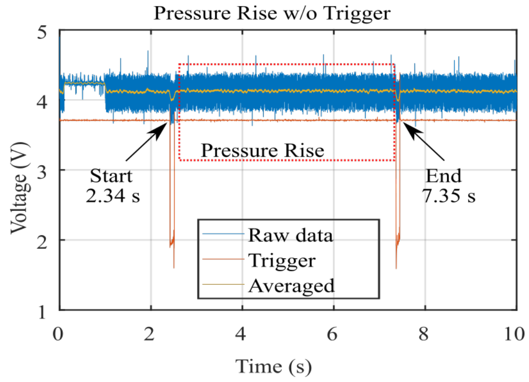

Fig. 9. Effect of pressure rise

The whole unfolding process (3 and 4 from the Fig. 1) from the beginning to the end are tested as one single process. During this process connecting cable capacitance effects are analyzed and discussed below.

In the third test (Number 3 from Table I and 3 and 4 from Fig. 1), the airbag is unfolded and the cable (conducting thread) is isolated from touching surrounding objects. In this unfolding event, non grounded (isolated from ground and surrounding objects) cable effect and trigger parasitic capacitance effect are studied. Fig. 10 shows the test result. A trigger is used to create parasitic capacitance as well as to trigger all data acquisition systems. The time axis has pre-trigger, trigger, and post-trigger phases. The airbag unfolds at -4.40 s and results in a voltage drop of 0.15 V during the whole unfolding event. This effect can be seen in the sensor signal. The test image of high-speed camera supports the statement where the unfolding at -4.4 s can be seen. Further, trigger voltage has parasitic capacitance hence the voltage changes. Its effect is also seen in the graph. When the trigger voltage drops from 3.00 V to 0, there is a voltage fluctuation in the sensor (0.2 V). The trigger also replicates the parasitic capacitance of a real case.

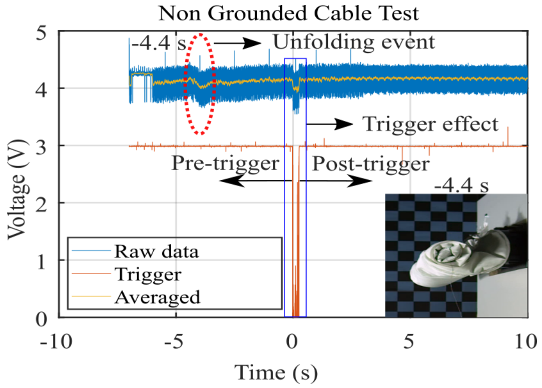

Fig. 10. Cable isolated during unfolding

Further, in the next test, the airbag is unfolded and the cable is allowed to move freely and touch the ground so that cable capacitance changes (Number 4 from Table I and 3 and 4 from the Fig. 1). Here ground is the earth not the electrical ground. Fig. 11 shows the plot of the sensor readings. There is more influence of the cable touching the ground. The voltage drop is higher than the isolated cable. This proves the requirement of isolating the cables. Fig. 12 is the short time window of the sensor signal from Fig. 11 synchronized with the images from the high-speed camera. At -6.10 s the unfolding event begins. The airbag opens at -5.95 s and reaches a stable unfolded position at -5.00 s. There is a voltage drop of 0.35 V during the entire event. This value is very high when it comes to occupant area calculation.

Therefore, from tests 3 and 4, it can be concluded that, cable isolation from ground or surrounded objects is crucial and parasitic capacitance has to be carefully considered during the real-time implementation. Otherwise, there can be misinterpretation of touch.

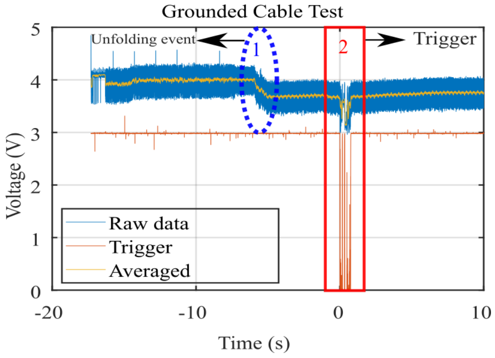

Fig. 11. Cable touching ground during unfolding

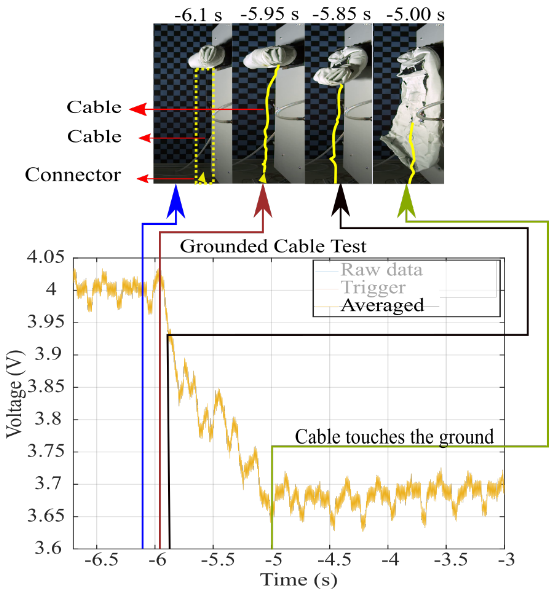

Fig. 12. Airbag unfolding and cable effect

Considering all the stated effects, three impact tests at 3.41 m/s impact velocity and 34 kPa airbag pressure are performed which also include the inflation phase and restraint phase from

Fig. 1 (Number 5 from Table I). In these tests, all phases from trigger to restraint phase are represented. Fig. 13 shows different phases and the sensor voltage drop for an impact test. From this test, it can be seen that the inflation of the bag has no effect on the sensor voltage and can be omitted from the algorithm. To analyze the impact phase further, the time window from -1 s to +1 s (from Fig. 13) is separated and represented in Fig. 14. As evident from the previous tests, when the airbag unfolds, there is a voltage drop followed by an inflation phase where the voltage is constant. During the impact, voltage drops from 4.11 V to 0.70 V; a difference of 3.41 V. This difference is proportional to contact area development over the time. Δt; the time difference between first contact and return from the sensor is 156 ms. This value is compared with the camera which is 165 ms. Thus considering the effects of the phases, the contact time and contact area of the occupant can be measured.

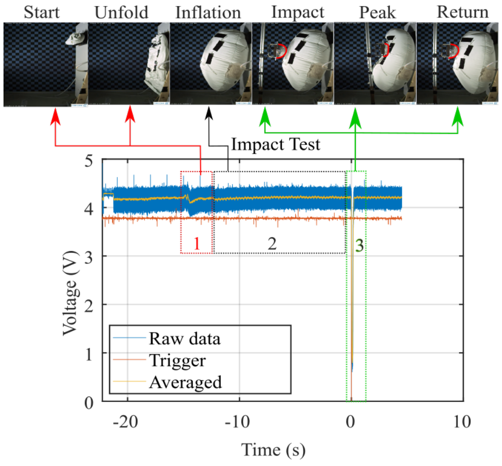

Fig. 13. Impact test with all phases

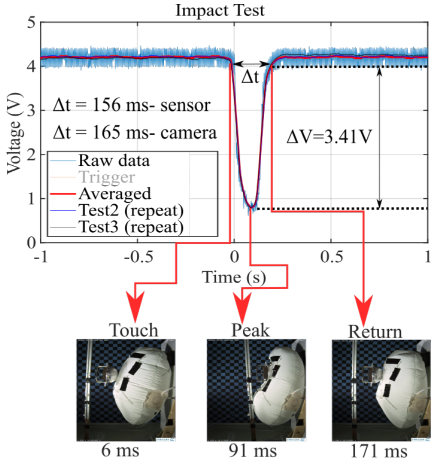

Fig. 14. Impact event

Fig. 14 shows the isolated time window of three successive reproducible tests. Test 2 and 3 follow the same behaviour as of the first test. The voltage drop is also identical along with the contact times. From the sensor voltage curve, the occupant contact area can be calculated. To calculate area, sensor calibration is required which is not under the scope of this paper.

V. CONCLUSION AND FUTURE WORK

The first step for the occupant contact detection with the airbag is to understand the behaviour of the sensor and the influencing parameters. The phase effects are the important parameters analyzed here. Avoiding charged objects in the vicinity of the sensor is one important conclusion. The sensor should be designed and installed in such a way that, during the deployment sensor should not come in contact with any objects except the occupant.

Considering the results of this work, in the next phase, occupant contact time, contact area and position of the occupant on the airbag will be measured and an algorithm to control the restraint effect will be developed.

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