AZD112 - Azoteq TWS Design Guide

Design guide for True Wireless Stereo (TWS) sensors offered by Azoteq's ProxFusion® range.
Design guidance and production specifications to consider.

Contents

1 Introduction

The aim of this document is to give a step-by-step guide on how to design capacitive and inductive sensors for TWS applications. The unique combination of sensor technologies available in a single chip enables designers to implement intuitive user interfaces, such as:

- Capacitive touch (tap for play/pause, hold or prolonged touch for ANC transparency/assistant)
- Capacitive slider (volume control, skip/prev. soundtrack navigation)
- Capacitive wear detect or grip detect (automatic play/pause/hold)
- Inductive force trigger (pressure sensitive tactile pinch button)

A summary of the design process is shown below:

Figure 1.1: Design Process Summary

The result of this process is to achieve the required performance of sensor features within the operational use cases required by TWS products of various designs.

The rest of this document is structured as follows: Chapter 2 outlines the specifications for Azoteq's user interface sensors for TWS products. Chapter 3 offers a high-level overview of Azoteq's TWS solution. In Chapter 4, designers will find various resources that are beneficial when designing TWS products and using Azoteq's products. Chapter 5 includes a design example of a TWS product interface utilizing the IQS7222A. Chapter 6 delves into the validation process of a TWS sensor design to ensure it meets the requirements. Chapter 7 covers the interface between a master MCU and Azoteq's TWS solution. Chapter 8 discusses important considerations for moving a TWS product into production. The Appendices include the Bill of Materials and mechanical details from the design in Chapter 5.

2 Design Specification / Product Requirements

This chapter outlines the key specifications for TWS sensors that need to be considered during design.

Sensor solutions are usually integrated IC-based subsystems fulfilling a subordinate or secondary controller status role. Due to the small form-factor of TWS products, designs are space-constrained and have extreme low power consumption requirements. TWS products mainly conform to one of the following two design types:

- Stem design
- Bud design

2.1 Mechanical specification

The mechanical specifications of both design types will be listed in the table below.

Table 2.1: Mechanical Specifications

Specification	Stem design	Bud design
Circuit substrate	Rigid FR4 PCB and FPC attachments	Rigid FR4 PCB and FPC attachments
Mechanical housing	Extruded (ABS or alike) plastic	Extruded (ABS or alike) plastic
Board area required (IC and external passives)	$\pm$ 70 mm^2 (single-sided component layout with WLCSP18 IC and 0603 SMD inductor)	
Slider length (typical)	$\sim$ 8 – 20 mm	$\sim$ 8 – 15 mm
Touch electrode area (min.)	$\geq$ 10 mm^2	$\geq$ 15 mm^2
Battery shape	Bar (stem located) or coin cell (round) type	Usually coin cell type

For the purpose of keeping design guidance concise without repetition, the rest of the information and discussions in this document will only focus on a **stem** design type.

2.2 Resolution specification

Sensor technologies (also referred to as sensor modes) offered are:

- Self-capacitive,
- Mutual-capacitive, and
- Inductive

Each sensor mode operates on its unique principle to offer a distinct set of qualities and trade-offs. Some are better suited to certain applications or implementations while others may provide different advantages which may be sought after for certain user interfaces (UIs) or features which deliver a certain user experience (UX).

The resolution specifications for each sensor mode are listed respectively in the table below.

Table 2.2: Resolution Specifications

Specification	Self-capacitive	Mutual-capacitive	Inductive
Touch / force channel SNR	$\geq$ 5:1	$\geq$ 5:1	$\geq$ 3:1
Wear channel SNR	$\geq$ 10:1	$\geq$ 10:1	n/a
Target amount	$\geq$ 500 counts	$\pm$ 320 counts	$\pm$ 500 counts
Delta magnitudes	50 to 500 counts	20 to 200 counts	10 to >1000 counts
Slider resolution	[(nr. of slider CHs) - 1] $\times$ 256/(slider length) pixels / mm		n/a

2.3 Linearity specification for sliders

Typical slider resolution and linearity specifications are listed in the table below.

Table 2.3: Slider Specifications

Specification	Minimum	Typical	Maximum
Number of channels	2 channels	3 channels	4 channels
Full coordinate/pixel range	1 pixel / mm	±256 pixels / channel	1000 pixels / channel or 4000 absolute maximum
Delta per channel	Above prox/touch threshold	∼50 to 200 counts	512 counts
Coordinate deviation	0 pixels / coordinates	±10% of full resolution	< min. gesture limits
Trimming calibration setup to reach upper and lower full coordinate range	0 pixels / coordinates trimmed	Residual coordinate amounts at the start and end of slider (>0 and <max. coordinate)	255 pixels / coordinates is the abs. max. amount that can be trimmed

Figure 2.1 shows a typical response of coordinate output from a single finger's travel over the length of a slider. The layout and number of electrodes (sensor elements or channels forming the slider) may be arbitrary, but for illustration purposes, four electrodes (x1 to x4) are indicated on the x-axis as an example. The deviation from perfect linearity in the coordinate output should be within acceptable limits to meet the linearity specification of the slider. Non-linearity and reduced coordinate ranges may occur inherently but should be minimised by conforming to slider specifications. The entire output coordinate range for a slider can be achieved with an additional post-processing trim step.

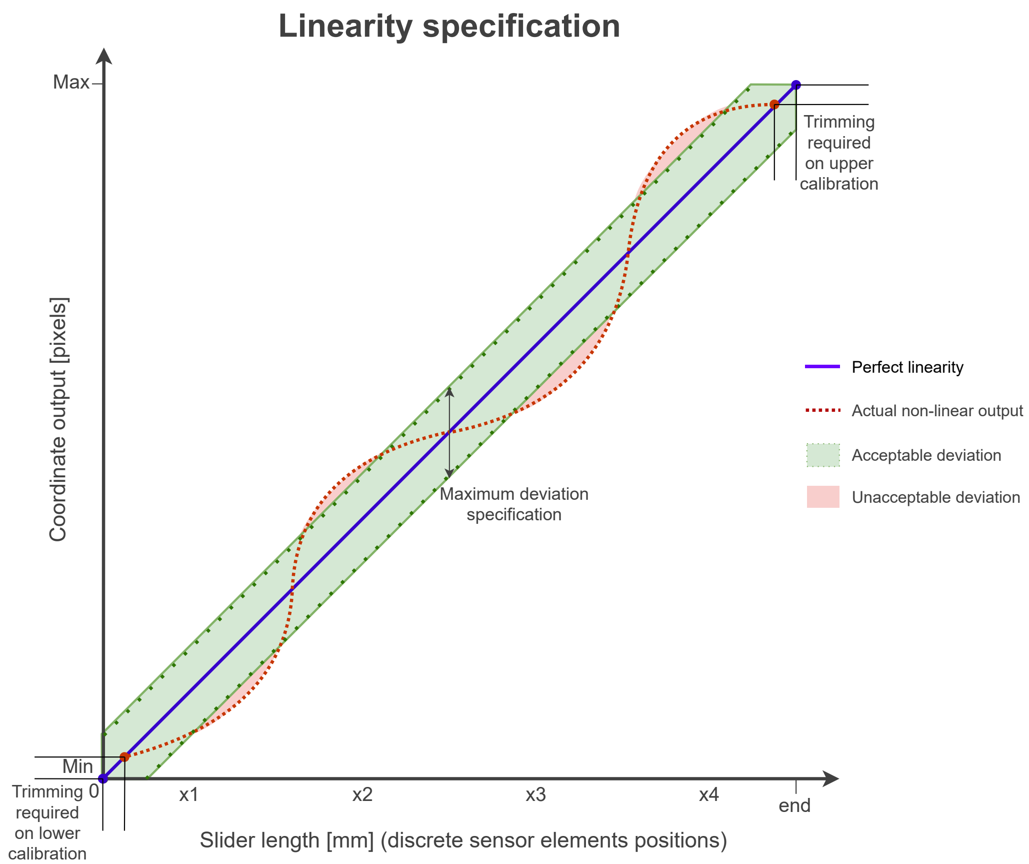


Figure 2.1: Slider Coordinate Linearity And Range Specification

2.4 Specification for inductive force sensor

This section requires the detail background guidance and further study of inductive sensing technology to clearly understand and formulate the proposed requirements. Please refer to AZD115 Inductive Sensing Application Note for fundamental detail regarding this technology. The mechanical specifications of a product will also dictate how a force, exerted on a particular TWS housing, will relate to the target/coil displacement achievable and thus measurable by an inductive sensor.

Typical TWS inductive sensor application travel and sensitivity specifications are provided in Table 2.4 below.

Table 2.4: Inductive Sensor Specifications

Specification	Minimum	Typical	Maximum
Inductance value	600 nH	1 µH	Limited by package and/or board space constraints
Resolution	±10 counts / 100 µm	±50 counts / 100 µm	±100 counts / 100 µm
Nominal target distance	0.2 mm	1 mm	< [coil diameter] / 2
Relative target deflection	10%	50%	100% or total distance of target separation
Transmitter frequency (Tx)	2 MHz	Higher for small inductance	14 MHz (F_{OSC}) recommended
Resonant frequency (LC)	Higher than the Tx frequency [$\geq$ +6% margin for F_{OSC} variation and tolerance over PVT]		
Metal target size	At least as large as the complete coil area		
Metal target material; resistivity	Copper, Nickel, steel, stainless-steel, aluminium (and plated or metal alloys); $<100\,\mathrm{n\Omega \cdot m}$		

Selecting the appropriate size inductor and tuning the resonant LC tank circuit can depend on numerous characteristic features required or naturally from a given set of limitations arising from the intended application or mechanical design. The reader is referred to the relevant technology and application notes for guidance and discussions regarding these trade-offs, concerns and design calculation procedures.

In TWS applications in general the aim would be to achieve an inductance value as high as possible while resonating the LC circuit with the highest available transmit frequency option. This will ensure that the passives (capacitors and resistors) needed are or substantial size, readily available and less affected from stray parasitic or coupling effects.

2.5 Specification for wear detect sensor

A wear detect sensor is a capacitive sensor that gives an indication of when a user is wearing/touching a product. The intention is that the sensor should accurately indicate when a user starts to interact with a product and when a user stops to interact with a product.

Wear detect sensors are associated with prox or touch activation states for channels/sensor which are in close proximity or direct skin contact for prolonged periods when a wearable product is worn (such as a TWS device in-ear).

Understanding the working environment and challenges associated with wear detect sensors will aid in understanding the related specifications. For further information and design guidance on wear detect applications, please refer to application note AZD110 (also listed in subsequent section 4: Design Resources.)

Table 2.5: Wear Detect Sensor Specifications

Specification	Minimum	Typical	Maximum
Number of channels used	One single channel (risk as there is no reference)	One or two pairs of channels (follower and reference combinations)	Limited by number of available channels and CRX pins
Sensor pad size	10 mm^2	$\pm$ 30 mm^2	$\geq$ 100 mm^2
Wear signal capacitance	200 fF		800 fF
Total sensor capacitance load (parasitic)	4 pF		10 pF
Charge transfer frequency (self-capacitive)	250 kHz	500 kHz	1 MHz
Transmitter frequency (mutual-capacitive)	500 kHz	1 MHz	2 MHz

2.6 Overlay specification

The specifications for overlays respective to each sensor type is given in the table below.

Table 2.6: Overlay Specifications

<table>
<tr><th>Specification</th><th>Self-capacitive</th><th>Mutual-capacitive</th><th>Inductive</th></tr>
<tr><td>Thickness</td><td>0.3mm to 5mm</td><td>0.3mm to 3mm</td><td>Any overlay thickness can be used as long as the distance of target to coil is maintained and relative deflection (decrease in gap size) is still achievable under the minimum required force</td></tr>
<tr><td>Material compositions</td><td colspan="2">Non-conductive dielectric (plastics, Mylar, glass etc.)
[excluding NCVM or similar metallic decorative finishes]</td><td>Compressible spacer (no permanent deformation)
moderate to high conductivity metal target</td></tr>
<tr><td>Adhesives</td><td>Thin double-sided film</td><td>Thin double-sided film / optical clear adhesives</td><td>Thin double-sided film</td></tr>
<tr><td>Coverage area</td><td colspan="2">Same size or ideally larger than the electrode / button</td><td>Metal required to be marginally larger than inductor / coil and composed as a single solid conductor (not multiple sections or a discontinuous pattern)</td></tr>
</table>

Overlay material properties and design should also be considered with respect to ESD qualification and the exposure of sensor pads through holes for speakers/microphones or near housing seams. Please refer to the next section for electrical specifications.

2.7 Electrical interface specification

The specifications for sensor electrical and interface design are listed in the table below.

Table 2.7: Electrical Specifications

Specification	ProxFusion series IC system implementation
Supply voltage (V_{DD})	1.8 V – 3.3 V
Internal regulation (V_{reg})	Digital and analogue domains (requires external decoupling capacitors)
Communication interface	I^2C (SCL, SDA) + interrupt / data-ready RDY (active-low output) signal for event indication
Master reset control	MCLR (some devices time share functionality on same pin with RDY)
Additional outputs	Optional. Up to 3× GPIO with custom configurable logic and output assignment
ESD protection	HBM up to class 3A and -B or IEC 61000-4-2 standard level 4 (contact and air discharge) System level qualification of finished product with the necessary protection can be achieved with the recommended series resistance on sensor (CRX) pins and the use of exposed ground traces and pours/floods for safe discharge. Extreme measures incorporates the use of TVS diodes to clamp nodes when and where necessary.
Radiated noise immunity	IEC 61000-4-3 standard test level 2 and 3 (3 V/m – 10 V/m) Appropriate capacitive decoupling and sensor series resistive elements (low-pass filter) component implementation and the placement thereof towards effective decoupling ground sites which are sufficiently stitched and commonly connected in a system are crucial for improved radiated immunity. Consider antenna placement and feed lines with higher energy flow
Current consumption	Application use of different sensors, UIs and response rate requirements may influence the current budget minimum allocation and brief periods of increased consumption. Optimisation of low power (sleep) current drawn should be minimised for extended idle periods and the usual small TWS battery storage and will typically be as low as in the sub 10 µA range (for an optimised ultra-low power reduced sensing state). Typically: Normal power: ±300 µA; Low power: ±150 µA; and Ultra-low power: ±10 µA

2.8 Operational environment specification

The specifications for sensor operational environments are listed in the table below.

Table 2.8: Operational Environment Specifications

Specification	Self-capacitive	Mutual-capacitive	Inductive
Typical product temperature range	-10°C to +60°C	-10°C to +60°C	-10°C to +60°C
Product operational relative humidity range	30- to 70 %RH	30- to 70 %RH	Same for internal circuitry, but can comply to a larger range for sealed housings
Usable charge transfer frequency range	125 kHz – 1 MHz	500 kHz – 4 MHz	2 MHz – 14 MHz (F_{OSC})

3 Proposed Solution

This chapter provides a high-level overview of Azoteq's TWS solution, including a system diagram, a typical mechanical stack-up, and a list of recommended Azoteq part numbers.

A dedicated sensor IC solution will be used as a peripheral node integrated into a TWS system. For the purpose of this document the design of a **stem** type TWS product will be discussed in detail.

The ProxFusion sensor IC series will showcase the benefits of multiple channels and combinational use of different sensor technologies all offered in a single package to reduce cost, power consumption, real-estate, bill of materials and embedded integration resources.

3.1 System Description

On a high level the system overview is comprised of three main sections:

- The user
- The sensor solution
- The host (main controller / processor / embedded system on chip)

The sensor slave controller (IQS device IC) is required to accommodate customisable setup(s) specific to hardware designs and UI requirements and will operate as required to sense, process and qualify detection of low-level measurement data while also doing the validation for user interaction events. Only when a valid event interaction is registered, the host will be interrupted to service and read the reported event state and detail via the dedicated communication interface, thus minimising the data transfer, latency, processing overhead and service priority (ISR) required so that other more important tasks on the host side (such as BLE connection and audio) can be handled with optimal/required resource allocation.

Figure 3.1 below provides a system block diagram of a generic TWS sensor implementation.

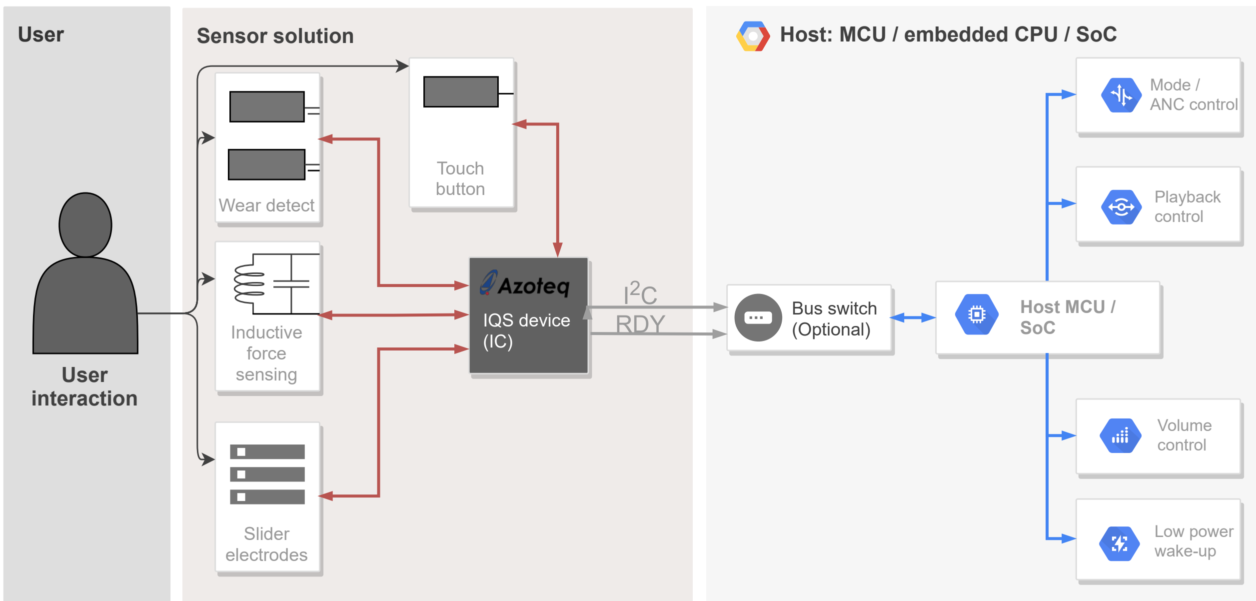


Figure 3.1: System Block Diagram

3.2 Assembly stack-up

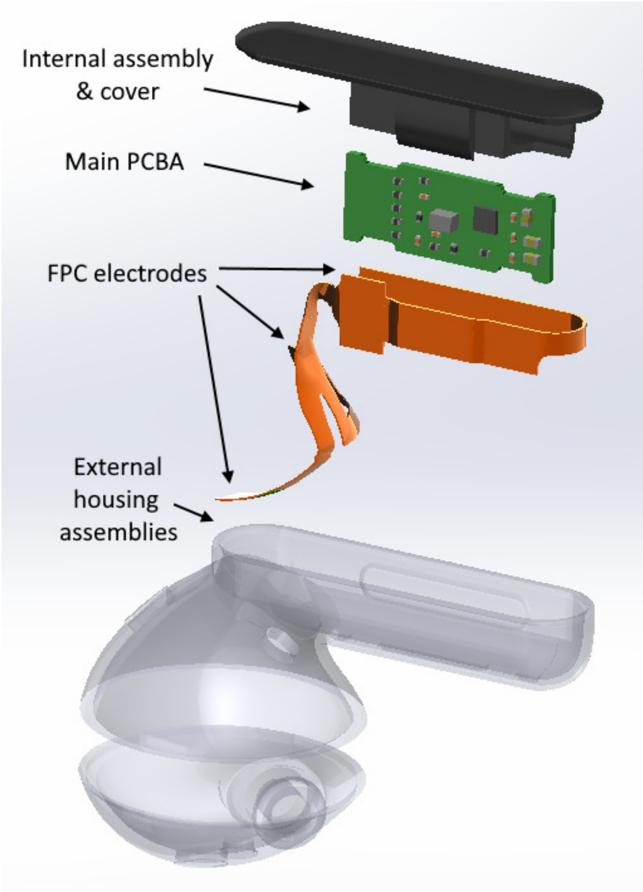


Figure 3.2: FPC Folded For Housing Assembly

3.3 Azoteq Device Selection Guide

The following listed devices are Azoteq's recommended TWS sensor solutions supporting proximity and touch detection, tap and swipe gestures, wear detect reference UI, inductive force sensing and onboard slider coordinate calculation (functionalities can be assigned based on any channel or group/pair of channel's data as needed).

- IQS7222A (WLCSP18 [1.62 x 1.62 x 0.5 mm])
  - Up to 7 self-capacitive touch / proximity sensing channels
    - up to 3 wear detection and reference pairs
  - Up to 9 mutual-capacitive touch / proximity sensing channels
  - Up to 4 inductive force sensing channels
  - Higher sensor flexibility with two ProxFusion sensor engines and 7 receiver pins

- IQS323 (WLCSP11 [1.48 x 1.08 x 0.345 mm])
  - Up to 3 self-capacitive touch / proximity sensing channels
    - 1 Wear detection and reference pair with a remaining self-capacitive input
  - Up to 3 mutual-capacitive touch / proximity sensing channels
  - Up to 2 inductive force sensing channels
  - Release UI implementation in addition to the reference UI to prevent stuck activations
  - Linearisation option for counts to achieve linear delta response

4 Design Resources

For all sensor design resources please refer to the Azoteq website: ProxFusion combination sensors

4.1 Datasheets, application notes and user guides

- IQS Device Datasheets
- AZD004 - Azoteq Sensing overview
- AZD044 - Azoteq MSL and Reflow specifications
- AZD125 - Capacitive sensing design guide
- AZD115 - Azoteq Inductive Sensing Application Note
- AZD015 - RF Immunity and detection in ProxSense and ProxFusion devices
  - Note: Azoteq ProxSense® devices include the ability to detect high levels of RF-radiation, and halt logic outputs to ensure false touch or proximity annunciations do not occur. However, this should be used as a last resort to ensure Radiated Immunity, as it effectively disables the touch functionality. We advise to only use RF-Detection of IQSxxx devices once all the guidelines presented here, as well as other remedial sources, have failed to result in Radiated Immunity as required.
- AZD102 - Series resistance limit of self capacitance charge transfers
- AZD110 - Azoteq Wear detect App Note
- IQS7222A GUI setup guide

4.2 Hardware design resources

- IQS7222AzzzQNR [QFN20] SCH symbol and PCB footprint
- IQS7222AzzzCSR [WLCSP18] SCH symbol and PCB footprint
- IQS323zzzDNR [DFN12] SCH symbol and PCB footprint
- IQS323zzzCSR [WLCSP11] SCH symbol and PCB footprint
- TWS stem demo hardware design files

4.3 Software, tools and example code

- Arduino Example code and user guide
- Graphical user interface software and tools
- CT210A Azoteq Configuration tool
- Linux generic IQS7222x driver available in the kernel release

4.4 Evaluation kits

- IQS7222A EV-kit resources
- IQS7222A EV-kit user guide
- IQS323 EV-kit resources
- IQS323 EV-kit user guide

5 Design Implementation

This chapter describes the design of the interface of a TWS stem-type product using an IQS7222A.

5.1 Sensor Design

This TWS stem design's sensor layout utilises two ProxFusion sensor technologies (capacitive and inductive) which are realised with two circuit layouts (a main PCBA and FPC electrodes). The latter hosting the electrodes that the user interacts with by indirectly touching/pressing the TWS outer housing where these sensors are located internally as showed in Figure 5.1 below.

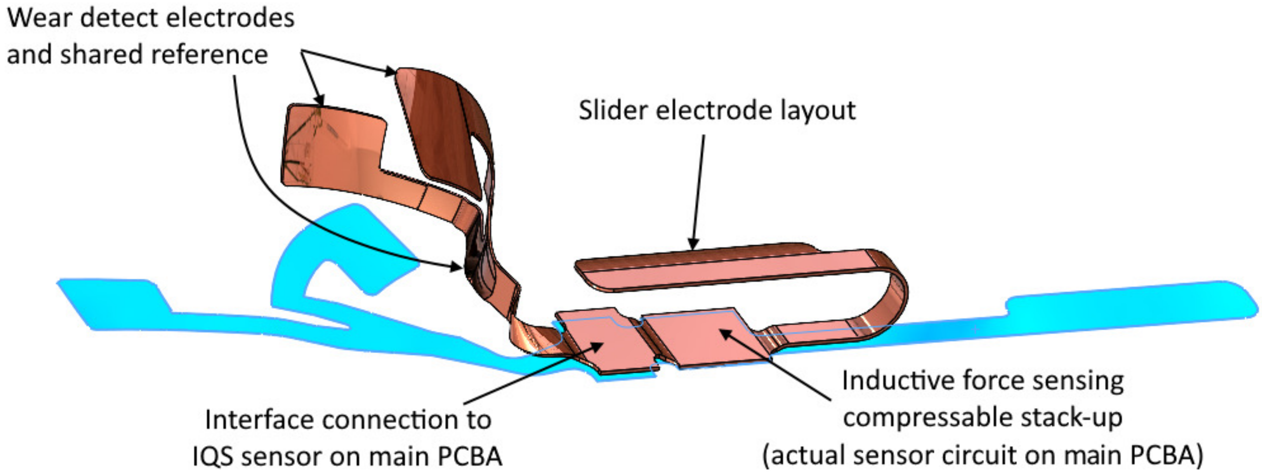


Figure 5.1: Sensor Design Layout

5.2 Circuit Design

A circuit was designed with the IQS7222A (WLCSP18 package) as per the schematic diagram shown in Figure 5.2 below. For the associated bill of materials (BOM), please see Appendix A: Table A.1.

5.2.1 Power supply decoupling and regulation

All IQS devices require external decoupling capacitance on their supply (VDD) as well as internal regulation (Vreg) pins. Please refer to IQS device IC specific datasheets for implementation and guidance for optimal component selection, size and placement/routing considerations.

5.2.2 Inductive circuit design

The implementation of this inductive force sensor will utilise an 0603 SMD inductor (L1) with an appropriate capacitance (C1) to form an LC resonated circuit which is biased/sensed with the necessary passive conditioning/decoupling components. For technical design guidance on inductive sensing and detail consideration please refer to AZD115.

A product specification may need to fulfill a certain minimum amount of force (stipulated in gram or Newton force) that will be applied with a pinch actuation on the force UI. It is the engineering product development team's responsibility to design a suitable housing or structural enclosure that is capable to compress/deform under such a force and return to its original state afterwards. Furthermore, the mechanical change/reduction under such a minimum force should be more than the smallest required deflection distance specification between target and coil that can be detected by the inductive sensor hardware. This will ensure a measurable count deviation that can be detected reliably as needed. In summary, the steps are:

- Force requirement (gram/Newton)
  - Minimum specification to satisfy the UX requirement
  - Needs to be incorporated into the mechanical design and translated to a quantitative deflection distance
- Mechanical design (µm - relative compression)
  - CAD used to ensure minimum distance is achievable
  - Consider material properties and assembly of different parts
  - Simulate final assemblies with CAD packages or doing finite element analysis
- Manufacture
- Test and validate
  - A micrometer can be used to characterize the target to coil movement's count response
  - Apply the minimum force and measure the resulting deflection distance with corresponding count delta
  - Use of linear actuators with accurate force measurement instrumentation can be applied with to great advantages for intricate controlled and repeated testing
  - Iterate until satisfactory results can be obtained to satisfy the force requirements

5.2.3 Capacitive sensor nodes

All the self-capacitive sensor inputs (CRX) are supplied with a standard series resistance to increase radiated immunity and will sense the connected electrodes accordingly (please refer to AZD125 for fundamental design discussions; AZD015 for considerations of radiated/RF immunity; AZD102 on using resistive paths higher than the recommended). The connections in this design are for:

- A two-channel slider, as well as
- Two wear detect channels, with a shared reference channel.

5.2.4 Connections

The required connector interface and test point implementations are provided to showcase typical product sub-assembly connections. Test points are convenient for design development, debugging and validation. The connections allow for the rapid testing of sub-assemblies for basic functionality and allows for the detection of any soldering issues before further assembly is performed. The product quality assurance can be done later in the production cycle.

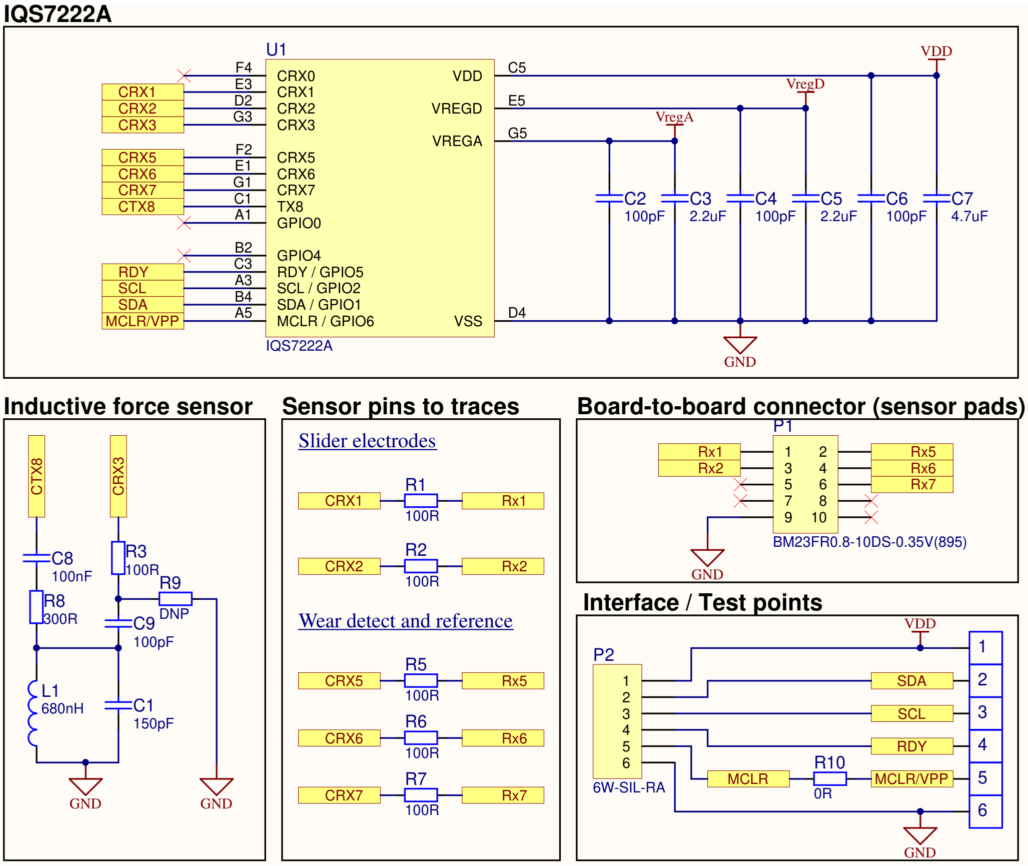


Figure 5.2: Schematic Design For TWS Sensor Solution

Not shown in the schematic of Figure 5.2 are:

- Pull-up resistances on I^2C lines (SDA and SCL) to system VDD
- Pull-up resistance on RDY (open-drain, active-low output interrupt signal) to system VDD
- Stabilisation capacitor (100 nF) on MCLR to GND (to prevent unexpected resets due to switching noise and jitter or MCU/SoC line noise or temporary sensor-hub peripheral sleep / shut-down)

These omitted passives form part of the larger system design when interfacing to a bus on a host MCU / SoC and should be considered in the specific implementation regard for system compatibility (i.e bus capacitance and clock speeds, reset or power supply- and management circuitry). Please refer to Appendix B: Table A.1 for a detailed Bill of Materials (BOM) of a typical implementation as for the above schematic design.

5.3 Main PCBA Layout Design

For the scope and purpose of this design document the main PCBA showcased here consists of merely the IQS IC and its required decoupling and passive components (apart from MCU/SoC and other product peripherals, audio, power etc.).

One can also place the IQS IC on a FPC and keep the inductor on the FR4 PCB or utilise a PCB/FPC trace coil. The reason for this is to make it possible to experiment with custom firmware on the OTP device. If a client requires a firmware change at some stage during the design cycle they can replace the FPC attachments much easier as a modular plugin at little cost and impact. The main board will contain all other electronics and peripherals so prototyping and debugging can be done with ease.

5.3.1 PCB Substrate

An FR4 rigid PCB is the preferred substrate choice for multi-layer routing with high precision SMT (pick-and-place) assembly of the intricate embedded circuit solutions typically used in TWS products.

Often the use of low-profile board-to-board connectors are convenient for simple plug-in assembly to interface additional FPC sensor-electrodes/power/audio circuitry.

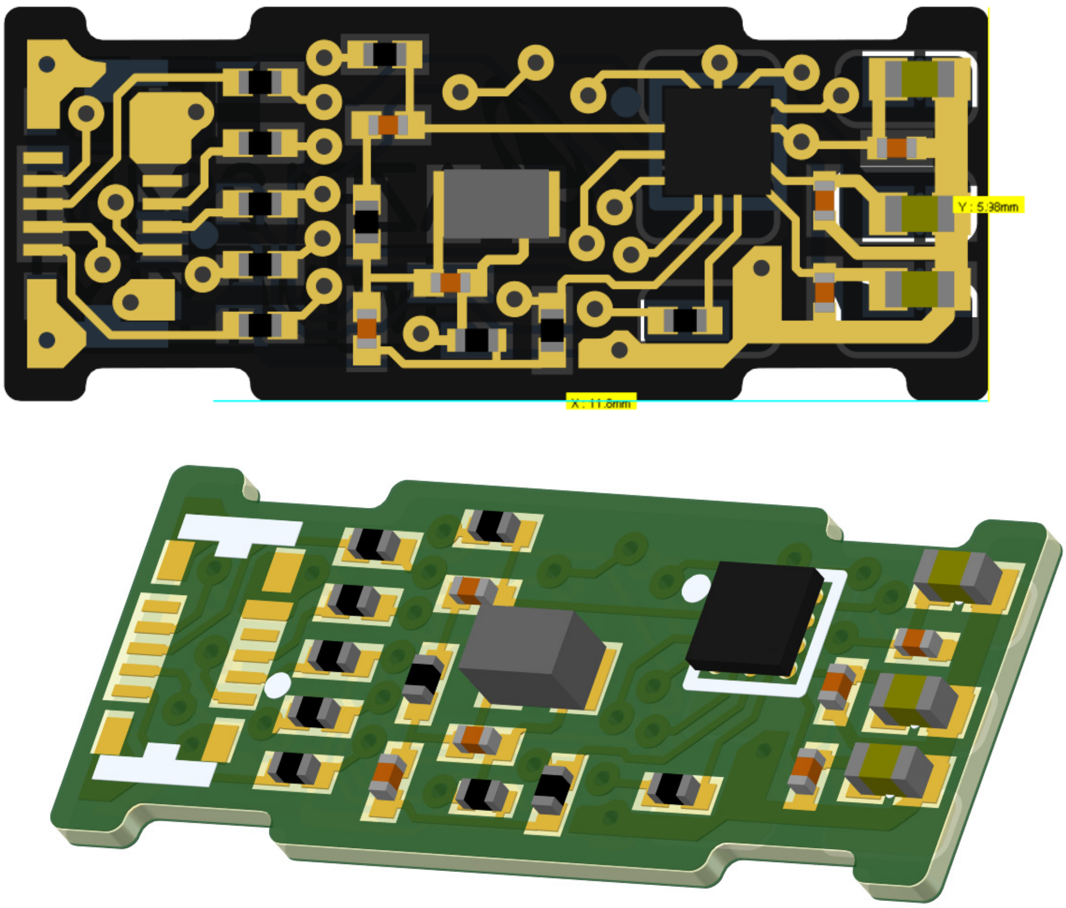


Figure 5.3: TWS Main PCBA Layout

5.3.2 Component sizes

The use of 0603M (metric) / 0201 (imperial) size components are nowadays an industry standard for TWS product assembly (otherwise 1005M/0402 package components are reasonable alternatives for large capacitors valued in the µF range). The SMD inductor required is slightly larger than the standard 1608M / 0603 footprint due to the wire windings and core size needed to reach its rated inductance value. Please see the next subsection for a discussion of the inductive sensor layout.

5.3.3 Inductive sensor

The inductance required to realise the force sensor solution can be one of two coil implementations:

- PCB/FPC routed trace coil (layout specific to requirement, available area/layers, rules etc.)
- SMD wire wounded coil (various parts exist)

These routing and other applicable coil design topics and considerations are discussed in AZD115.

The SMD part used in this design for component L1 is a wire-wounded inductor with a ceramic core and a resultant 680 nH rated inductance value. The use of a ceramic core component ensures that the inductance field is not affected by close proximity magnets or varying magnetic fields often present in TWS device and docking/charging cases.

PCBA (carrying the inductor) and FPC (metal target) alignment within the TWS housing structure assembly is crucial for optimal inductive force sensing. The SMD inductor or PCB coil trace winding is required to be assembled centered and within a small but consistent separation distance from the target conductor. To secure these features and prevent the PCBA from moving / shifting under the applied pressure forces, the PCB outline / profile was keyed with notches to fit into a matching internal housing structure in order to keep it fixed in place.

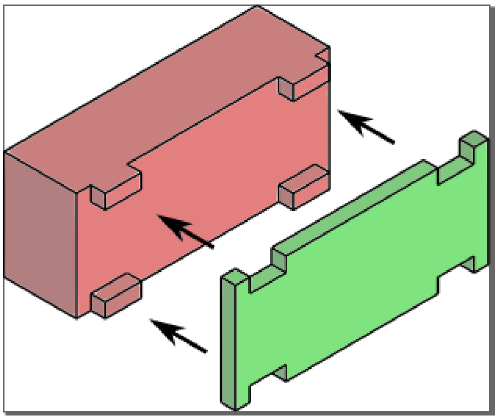


Figure 5.4: PCBA Assembly

5.4 Electrode FPC Layout Design

The electrode is manufactured using a flexible printed circuit (FPC) due to the intricate bending and curved surfaces electrodes are normally required to attached to.

5.4.1 FPC substrate considerations

It is beneficial to limit the population of integrated circuit components or to minimise the amount of passive and/or discrete electronic components on accompanying FPCBs to reduce the requirements for testing (probing or optical inspection) as well as rigid stiffened back-ends. The risk of damage during reflow and assembly are higher for FPC and the appropriate use of stiffeners behind component areas are usually mandatory but can aid in the assembly process by demarcating the areas that should not bend and simplifying assembly into prepared housing cavities. Nonetheless, this complicates FPC design and testing and usually comes at a higher risk and cost apart from consuming more board area as opposed to FR-4 PCB with double sided component placement.

5.4.2 Electrodes and adhesives

The electrodes are usually supplied with thin-film double-sided adhesive. For this purpose it is important to prepare the necessary alignment holes, notches or fiducial markers. For intricate shapes of FPC board outlines it is sometime common practice to specify a tissue carrier type adhesive material (with superior die-cut properties) which will also be die-cut simultaneously during depanelization of FPC modules for mass production. In the same fashion, FPC designs with SMT components required to be reflowed before depanelization, may be preassembled with special adhesives with superior temperature tolerance properties which are safe to be exposed to high reflow temperatures without risk of delamination or a reduction in adhesive strength capability afterwards.

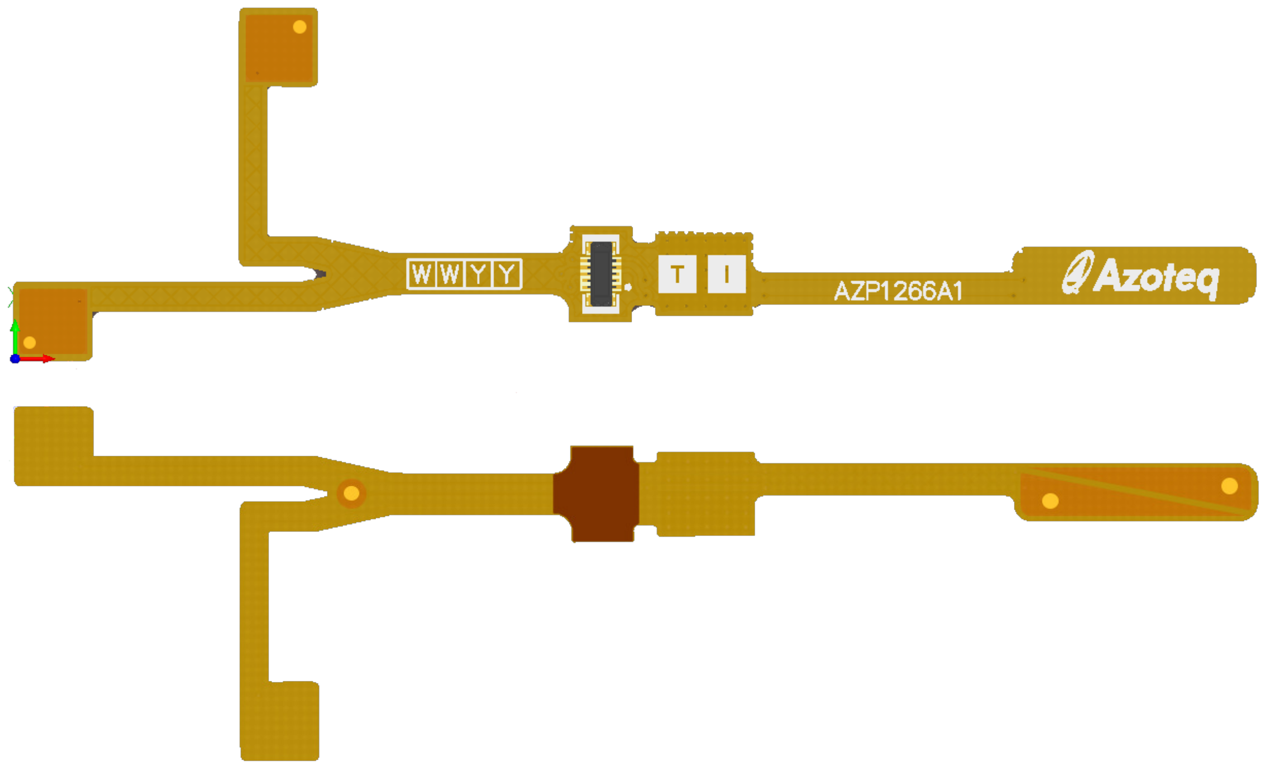


Figure 5.5: FPC Layout

5.4.3 Connectors, stiffeners, test points and silkscreen printing

Figure 5.5 above show the top and bottom view of the FPC electrode used in the TWS stem design. The only part required to be surface-mount assembled and soldered is the board-to-board connector which is situated on a polyimide stiffener (do not use metal stiffeners where capacitive sensor traces (CRX nets) are transferred/routed). Silkscreen printing do not affect capacitive sensors and may be used over pads or for assembly alignment references. It is however advised to provide solder mask/-coverlay openings and test-points on the furthest ends of connected traces for post manufacturing electrical/flying-probe test purposes.

5.4.4 Slider electrode design

Slider electrode patterns may differ depending on the length, width and resolution requirements. The specific pattern also needs to be considered and designed suitably to the overlay material and thickness while also considering the diameter of typical fingers on the contact surface covering the electrode(s). Mutual-capacitive sliders may provide superior signal stability and finer resolution but requires careful design with Rx and Tx pairs. TWS applications are extremely space-constrained and therefore it is challenging to fit multiple sensors traces within small FPCs. Self-capacitive electrodes for touch and sliders are simple to design and easy to set up. For sliders it is desirable to have a gradual transition in the output coordinates as the user swipes from the one side of the slider to the other side. This requires the manipulation of sensor pads and the appropriate use of signal ground to obtain an output signal that exhibits a gradual transition from one channel to the next. The IQS sensor solutions offer multiple configuration options and processing techniques to aid in slider performance optimisation. As and example mentioned earlier: The achievable coordinate range can be mapped to a specific desired coordinate range through on-chip trimming calibration where the unreachable coordinates at the edges of the slider are artificially trimmed away and the remaining achievable coordinates are stretched to provide the entire output coordinate range as needed in a system. For detail guidance on capacitive slider designs please refer to application note AZD125. Figure 5.6 below shows an example of the most minimalistic slider design for a mere two channels.

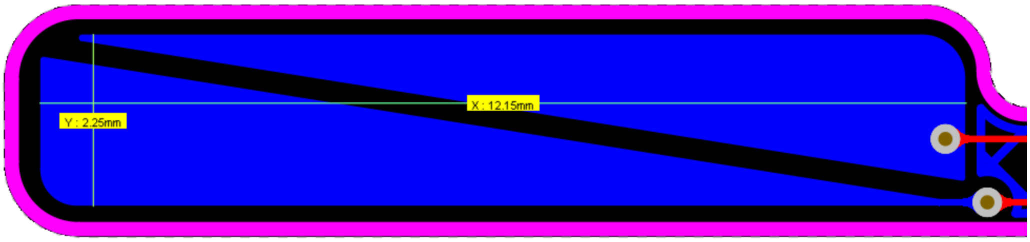


Figure 5.6: FPC Slider Layout

5.4.5 Inductive metal target design

The FPC serves as the carrier for a metal square that is used in the inductive sensor to induce eddy currents. This piece of metal was designed as a top layer pour/flood connected to system ground (GND). For mechanical and RF interference design optimisation the flood was repeated on the bottom layer and suitably via stitched to prevent any floating or long loops / paths to eliminate any possible noise concerns. It is mandatory that:

- The target should be larger than the coil to effectively cover the majority of the electromagnetic field lines
- The pour/flood should be a solid plane with low resistivity to easily allow the flow of Eddy currents

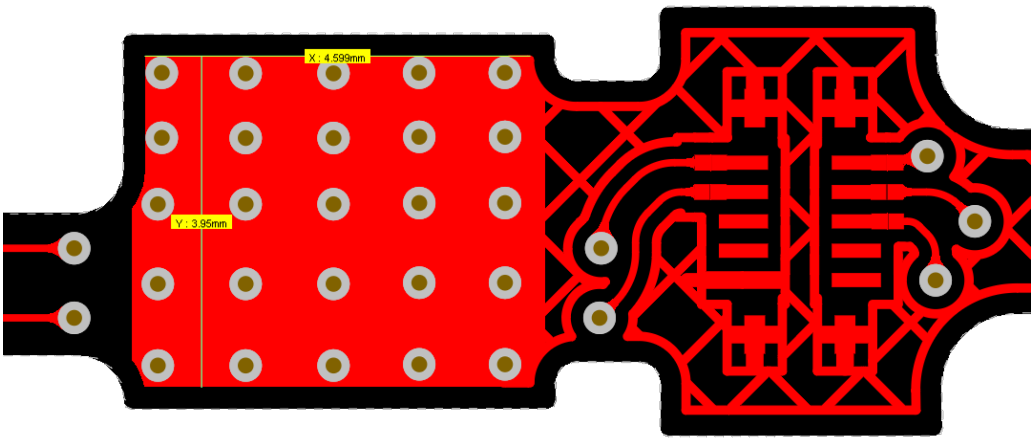


Figure 5.7: FPC Metal Target Design

5.4.6 Product assembly planning and tolerances

The design process of PCB and FPCB layout should be done in the preconceived fashion to accommodate how the product assembly will take place, and how mechanical tolerance can be minimised or taken into account to ensure production consistency. The IQS devices have internal sensor algorithms (automatic tuning for self calibration) to account for and equalize minor manufacturing and assembly inconsistencies in order to try and maintain sensitivity, however this will always be limited and related to the hardware quality.

Complex considerations such as mechanical wear, product robustness over life-span and material degradation etc. should also be kept in mind especially when the functionality of sensors are strongly related to the mechanical behaviour and movement such as in the case of an inductive force sensor. Please refer to the next section on these related topics.

5.5 Mechanical Design

Refer to Appendix B for mechanical assembly drawings generated by computer-aided design (CAD) software for the TWS stem design.

5.5.1 Inductive

An inductive sensor contains an IC, a resonator and a metal target. The sensor IC drives the resonator to create an electromagnetic field that can be influenced by the user. The user can move the metal target closer to the resonator by applying force to the housing of the product. The sensor IC measures changes in the current in the resonator. The IC can detect changes in the distance between the metal target and the resonator as this results in changes in the sampled current. It is important that the housing of the product returns to its original shape after the user stops to apply force. Due to the intricate nature of TWS designs and the small associated inductance values, mechanical simulation is advised to be executed prior to manufacturing. Generally, TWS products are enclosed in minuscule housing parts and have delicate form factors and features. It is therefore common that the housings of TWS products do not allow for a lot of mechanical movement. In order to compensate for the minimal available mechanical movement, the metal target should be positioned as close as possible to the resonator. In Figure 5.8 below, the CAD design of the TWS assembly is shown with the distance between the top of the SMD inductor (L1) and the FPC metal target indicated.

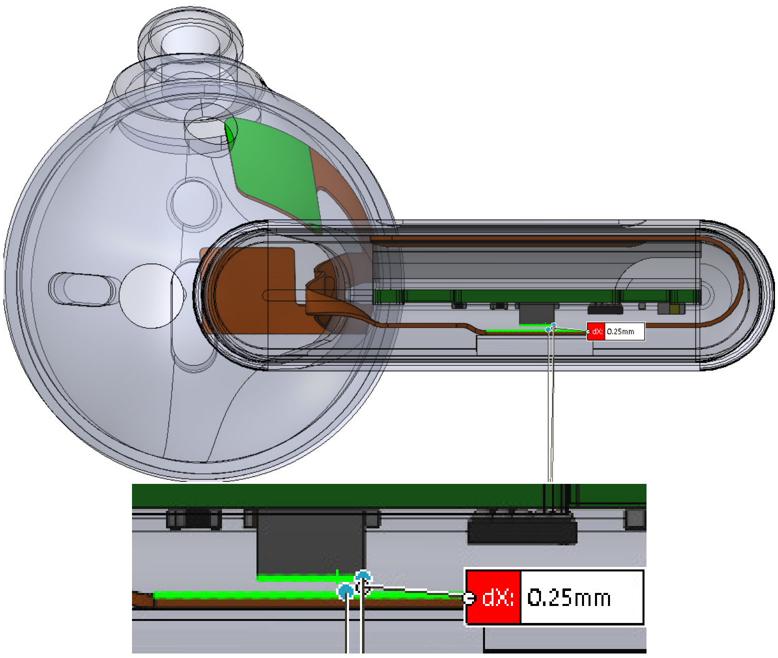


Figure 5.8: Inductor To FPC Metal Target Separation Distance

Figure 5.9 below shows how the FPC (transparently sketched) should ideally be positioned perfectly centered over the inductor (L1) on the main PCBA.

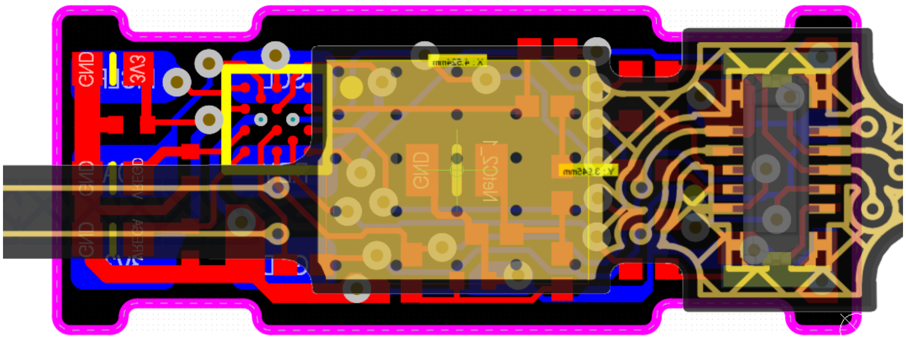


Figure 5.9: FPC Metal Target Alignment Over Inductor

Figure 5.10 shows the result of a mechanical structural analysis of the outer walls of the housing when a user applies a pinching force.

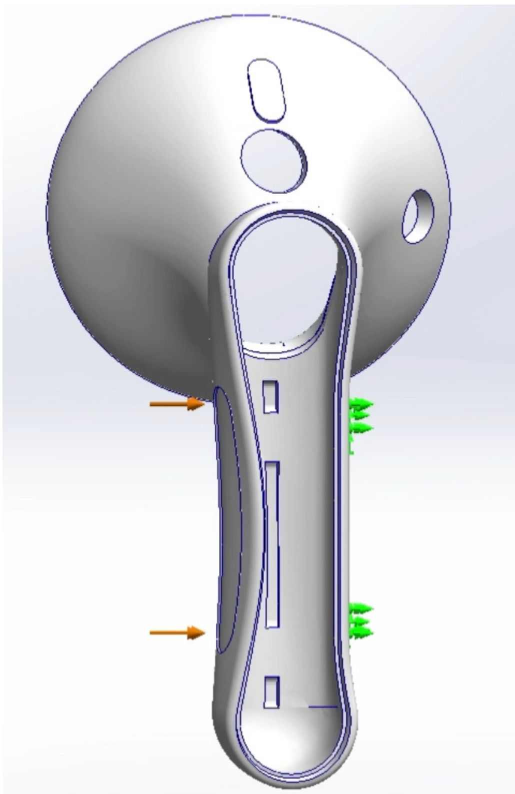


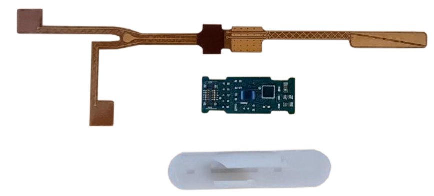
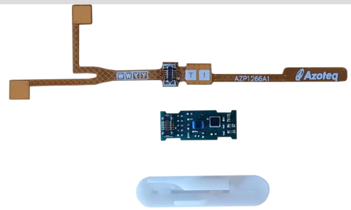
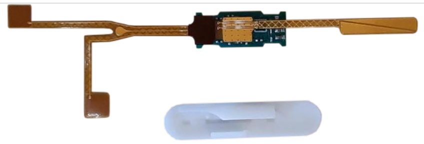
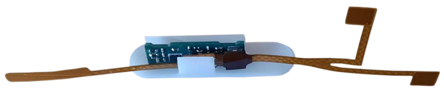
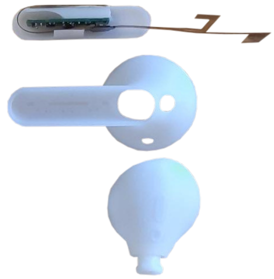
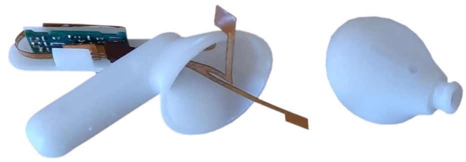
Figure 5.10: TWS Housing Deflection Under Compression Force

The analysis showed that a force of **0.49 N or 50 g force** would theoretically deflect the housing wall by **0.041 mm or 41 µm**. This is a compression or reduction in gap distance of 16.4% from the nominal 0.250 mm gap when no force is applied. Thus the design fulfills the minimum requirement for relative target deflection but needs to be confirmed practically.

5.6 Manufacturing

The assembly procedure of the stem type TWS design example is described in the table below.

Table 5.1: TWS Stem Assembly Procedure

Assembly step	Front view	Rear view
1. FPC, PCB and inner structure parts		
2. FPC plugged into PCB via board-to-board connector		
3. PCB fastened on to inner structure (FPC target secured in front of inductor; FPC slider tail is folded back and adhered on rear)		
4. Inner assembly and external housing parts (FPC wear electrodes fed through main housing's neck beforehand)		
5. Inner assembly fitted into external stem housing (slider fitted against external wall where finger guide/indent is located)		
6. FPC wear electrodes positioned and attached to speaker housing shells (pads securely glued in place with copper side facing outward)		
7. Completed assembly		

5.7 IC Setup

The graphical user interface (GUI) is a powerful support/design tool to simplify the process of configuring the IQS device with the parameters required for optimal performance for customer-specific hardware.

An introduction on how to use Azoteq's debug and display tool can be seen in this video.

The latest GUI can be obtained from the relevant product page on the Azoteq website as listed in Chapter 4.

5.7.1 Cycle setup

The cycle setup is shown in Figure 5.11 below. Applicable use of each CH/sensor is labeled with red text in each cycle. The sensor pins assigned and implemented in hardware are now selected for use specific to the channel that will be converted in that cycle. Yellow highlighted CHs/sensors are converted by ProxFusion sensor engine A (*CRX0-3*), while green highlighted CHs/sensors are converted by ProxFusion sensing engine B (*CRX4-7*).

Please note:

- *Self-capacitance* sensors (*PXS mode* setting) need to select the *CTx* boxes in cycle settings as well as the corresponding *CRx* boxes in CH settings for use as receiver input pins.
- For *Cycle 4 - CH4* setup in *mutual-inductive* mode, *CTx8* is selected alone as the transmitter pin (Tx) and *CRx3* is selected as the Rx pin in *CH4 settings* tab (see Figure 5.12 further below).

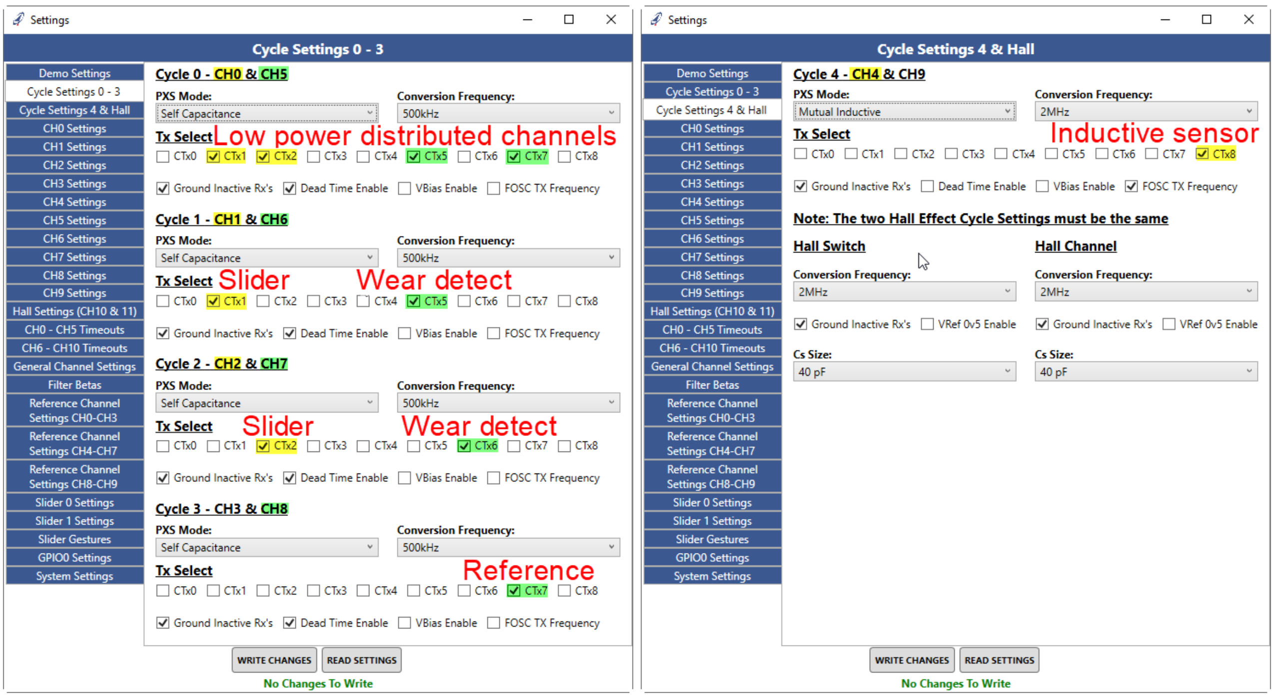


Figure 5.11: Cycle Setup

Channels which are not in use (those not highlighted in the above image) are disabled and will not be used for measurements.

5.7.2 Channel settings

Each channel will be set up according to its own requirements. For further clarification of each setting please refer to device datasheets and the relevant GUI setup guide.

Specific mentioning of the inductive sensor's CH4 settings are noteworthy and shown in Figure 5.12 below. The Rx selection (*CRx3*) can be seen to operate alongside the Tx (*CTx8*). For inductive sensors it is recommended to set the same base and target value as this will result in the ATI algorithm choosing the optimal multiplier- and divider values while using the minimum amount of compensation. Compensation should be minimised to improve the temperature stability. The inductive sensing design example at hand will exhibit an increase in counts when a target conductor moves closer to the inductor. This necessitates that the *Invert* logic directionality needs to be set/activated for CH4 to trigger when counts > [LTA + thresholds].

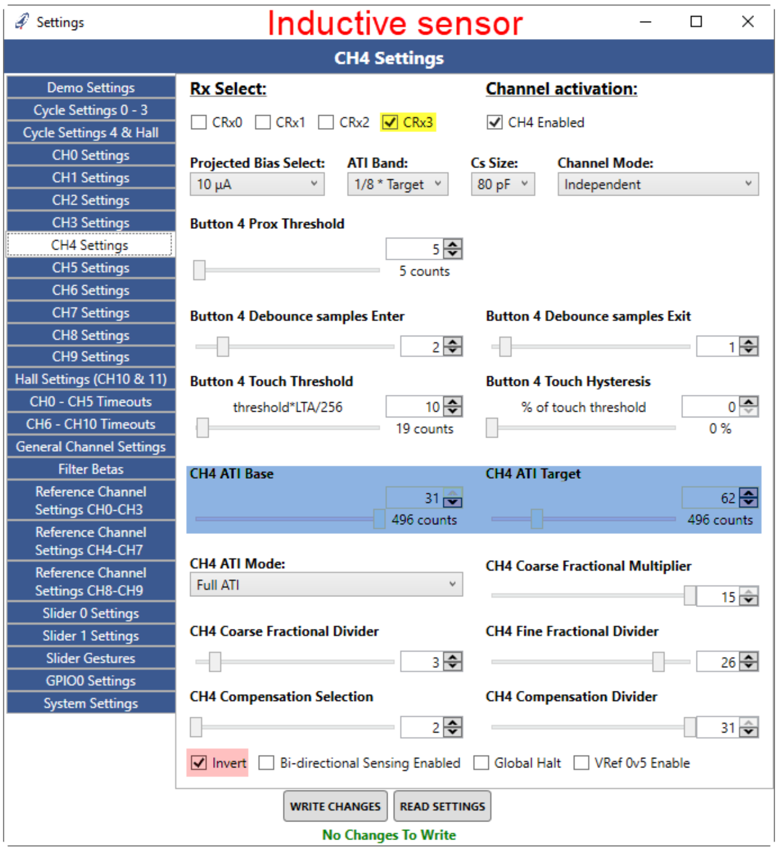


Figure 5.12: Channel 4 Settings: Inductive Sensor

5.7.3 System settings

For this TWS design example, a possible power mode setup is given in Figure 5.13.

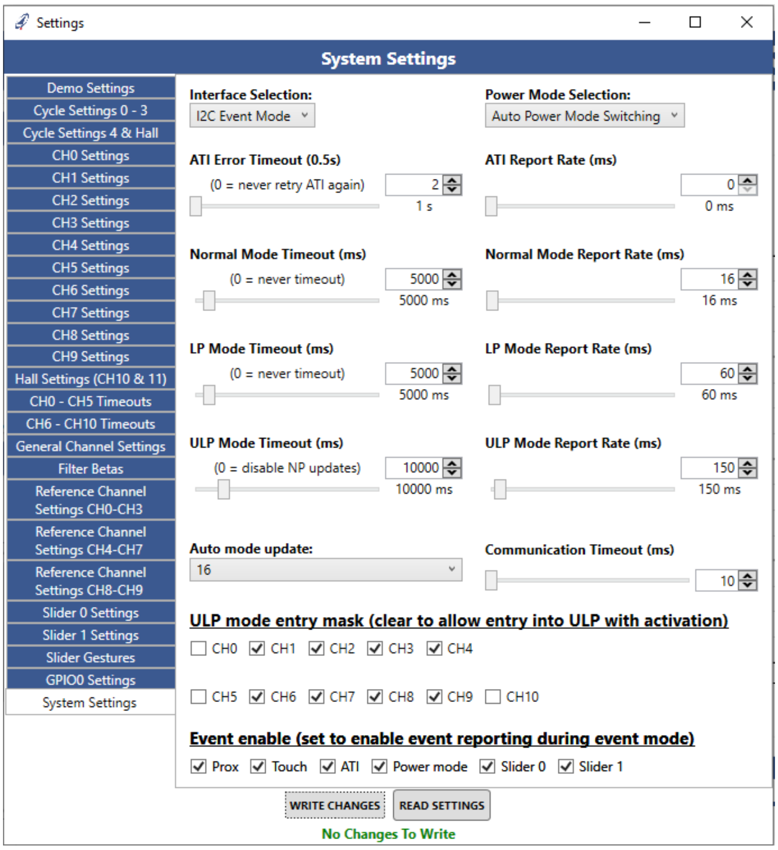


Figure 5.13: System Settings For Interface And Power Mode Setup

5.7.4 Reference and follower channel setup

For this TWS design example, a single reference channel (CH7) was configured to adjust the long term averages (LTAs) for the wear detect channels (CH6 and CH8). The concept of a reference channel is to have a sensor that is similarly routed and set up as its follower channels. All are subjected to the same environmental influences but the reference are purely tracking the environment and thus shouldn't be affected by the user in any way. The device then uses the measurement information from this reference channel and through customary assignment apply a weighted change or compensation to the long term average value of the followers. In this example the wear detect channels are adjusted during their activation states as this can persist for a long duration. The settings showed in Figure 5.14 applies a 125% weight adjustment to CH6 and a 150% factor to CH8.

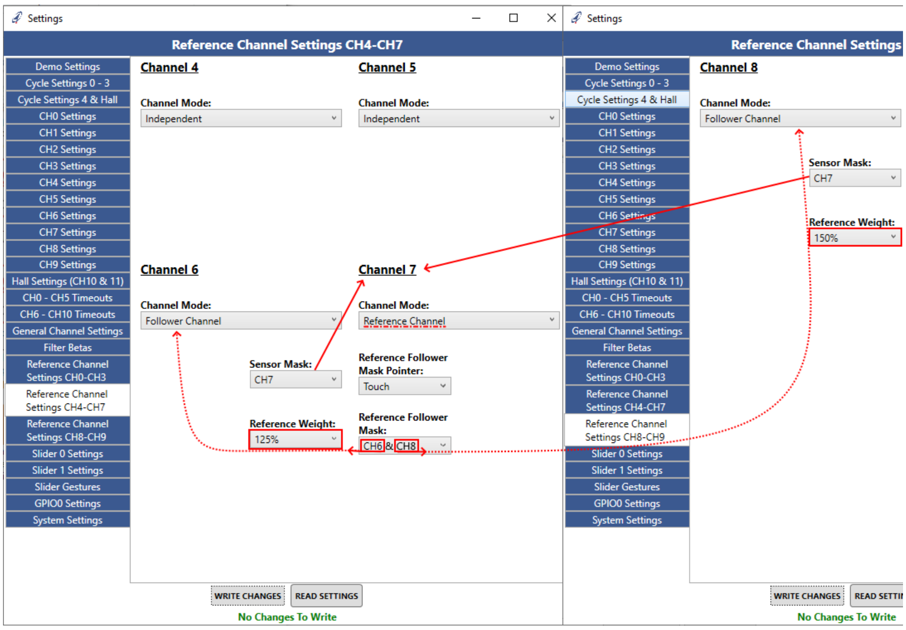


Figure 5.14: Reference Channel Settings For Environmental Compensation

6 Design Verification

This chapter describes the general procedure that should be followed to validate whether a design meets the original requirements.

6.1 Hardware connections for evaluation

Connect the power, programming (VPP - optional / as needed), I^2C and RDY lines of the IQS7222A to the CT210A USB dongle as shown in the table and in the figure below. Now connect the CT210A via an USB-micro cable to an available USB port on a PC.

Table 6.1: CT210A Pin-out

IQS Pins	CT210A Pins
GND	Pin 1
VDD	Pin 3
VPP	Pin 5
SDA	Pin 7
SCL	Pin 9
RDY	Pin 10

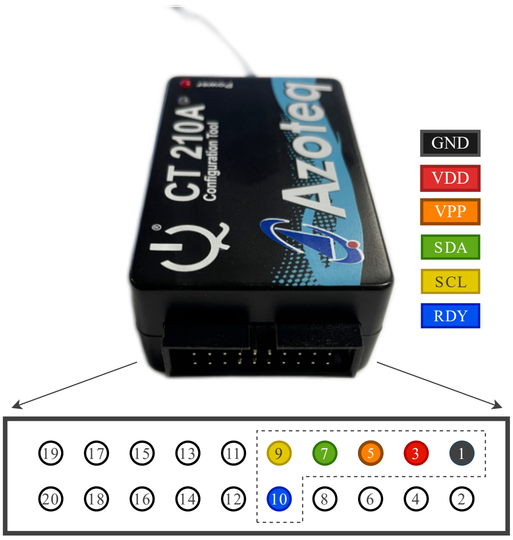


Figure 6.1: CT210A Power, Programming (VPP), I^2C And RDY Connections

The typical procedure to evaluate a device is as follows:

- Open the device-specific GUI software
- Initiate the streaming of device data by clicking the "START STREAMING" button
- Load the application-specific configuration settings using the "IMPORT H FILE" button, or configure the device manually by pressing the "USER SETTINGS" button and using the various options available in the submenus
- Ensure that the ATI algorithm has executed correctly after the changes in the previous step have been applied
- View the channel or system response by means of the bar, scope or event indications

- Specific operating modes (such as low power sampling or event mode operation) can also be induced for example to measure currents or to monitor I²C and RDY logic behaviour and event activities.

For further detailed information on the related device and/or GUI support please consult the necessary documents as listed in section 4.

6.2 Response Output

Evaluating the response of a sensor in real-time is beneficial for rapid setup, tuning and prototyping.

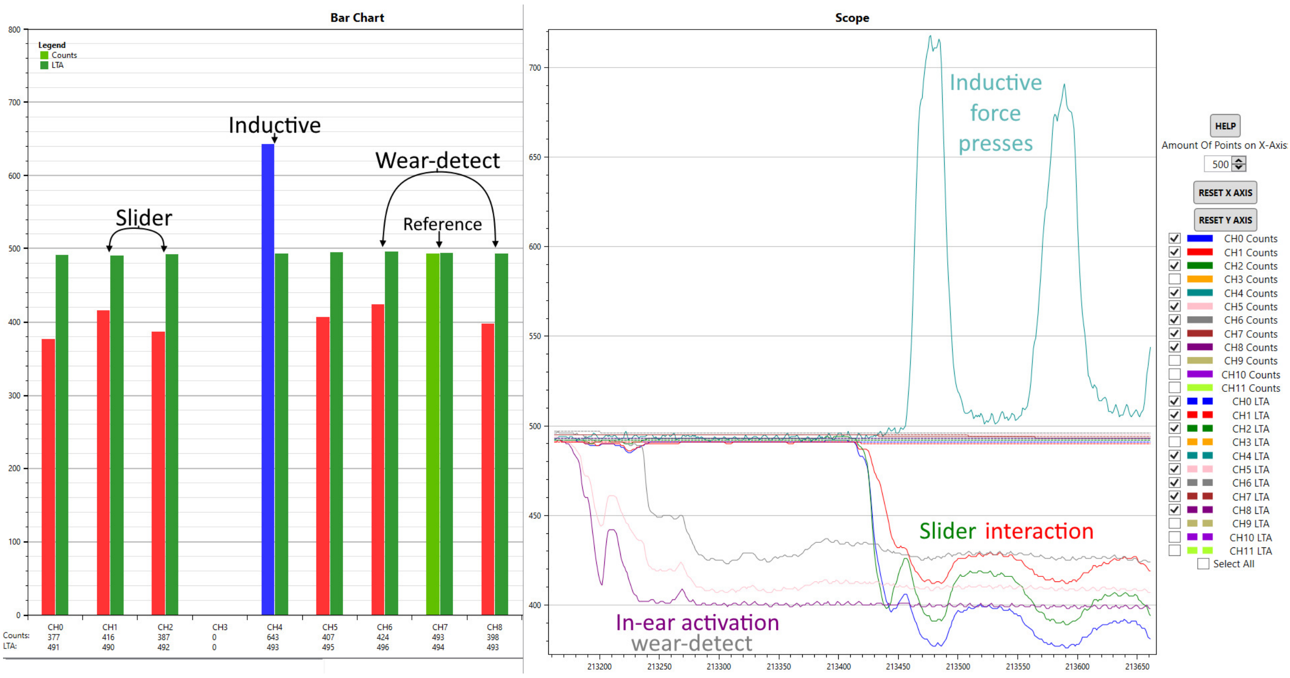


Figure 6.2: General GUI Bar And Scope Output For Count And LTA Data

To thoroughly evaluate and analyze the response of the sensors, it is recommended to gather sample data through logging sessions. These sessions may involve extended activation periods, temperature or humidity variations, or other stimuli, depending on the specific use case or qualification being examined.

6.3 Inductive force measurement

A precision linear actuator was used to test the response of an inductive force sensor. The sensor was mounted in a suitable test jig. Care was taken to ensure that the TWS was fixed so that the measured deflection and force was purely from the bending of the TWS housing under the force applied. Figure 6.3 below provides a summary of the measured data.

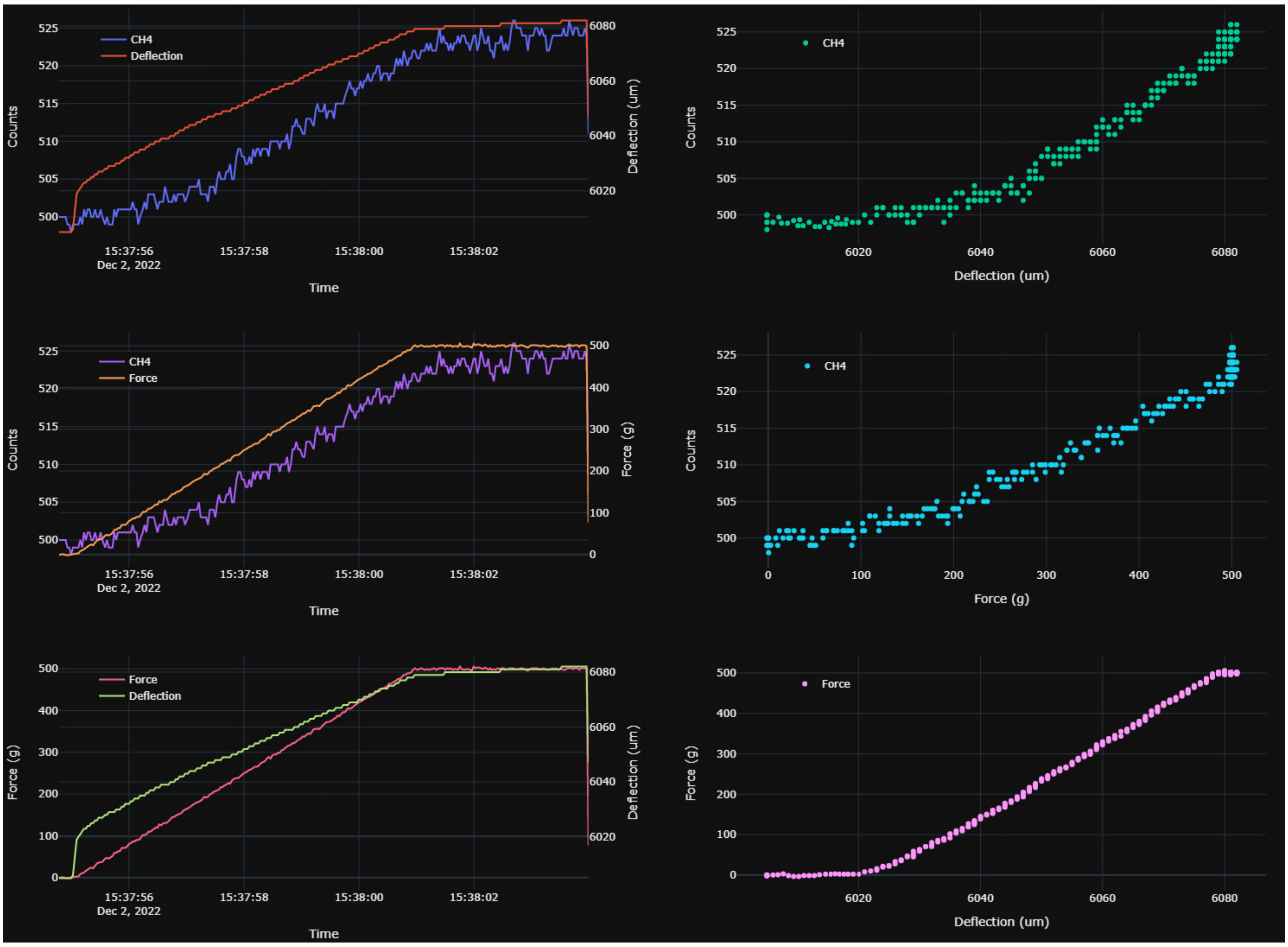


Figure 6.3: Applied Force With Measured Deflection And Count Output Response Graphed Against One Another

6.4 Linearity Tests (slider coordinates)

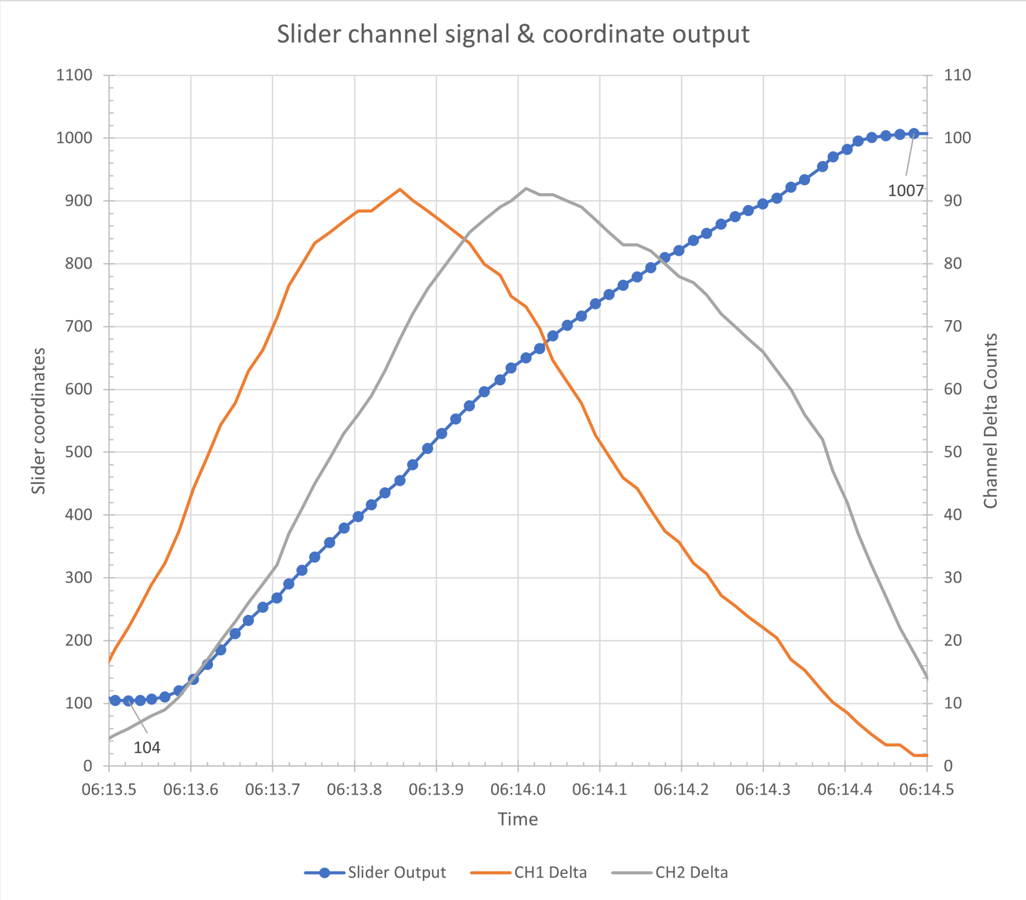


Figure 6.4: Slider Coordinate Output Graphed With Slider Channel Deltas

The above results obtained for the slider channel's delta and processed coordinates for a finger swipe over the total length of the slider are within specifications. Optimisation can be done by trimming the lower residual coordinate (∼104) in order to reach zero for a finger placed on the slider's absolute lower starting point by means of increasing the lower calibration setting.

6.5 Wear detection

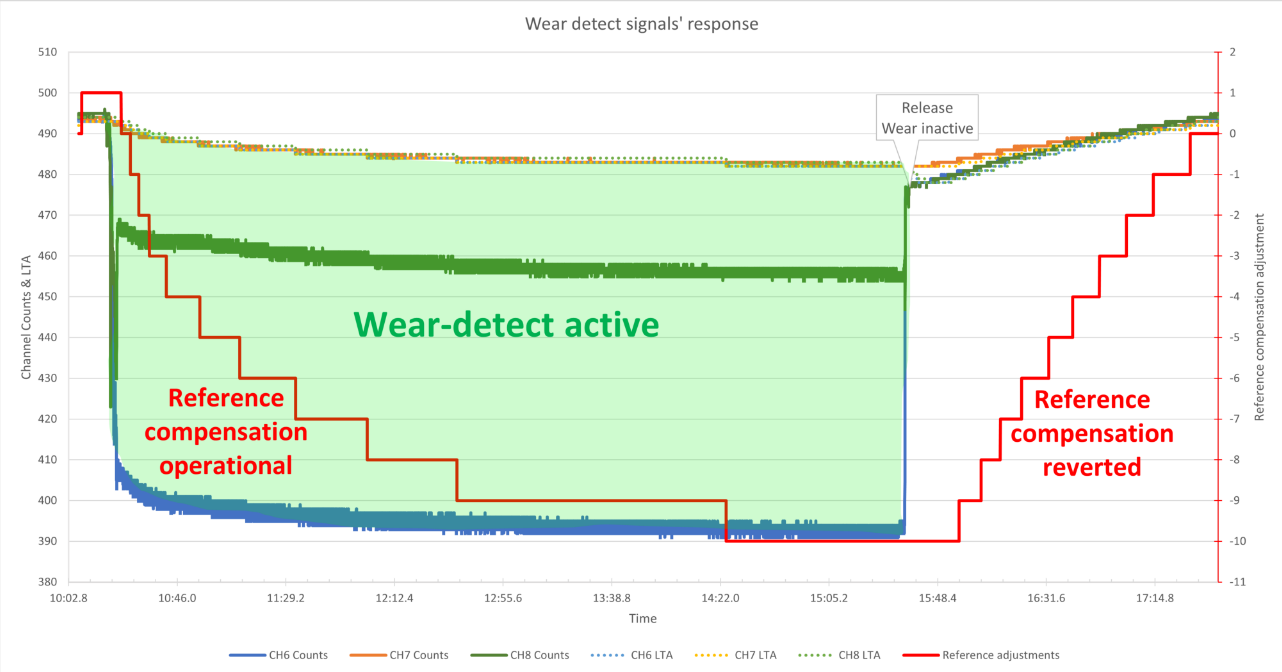


Figure 6.5: Wear Detect Output Graphed With Reference Compensation Adjustment Shown

The graph depicted in Figure 6.5 above shows the counts and LTA responses for the two wear detect channels (CH6 and CH8) with the common/mutually used reference (CH7). Added to the graph's secondary axis (right-hand side) and shown in red, is the number of counts the reference channel deviated and adjusted the LTAs of the wear detect channels. The adjustment is applied during the active wear detect state (coloured in green, when filters are normally halted) to account for the environmental drift during this 5 minute in-ear wear period. One can observe that the difference between the count and the LTA values remain fairly consistent throughout the experiment and that the same magnitude of reference compensation is reverted after the release / inactive state occurrence.

6.5.1 Temperature and humidity tests

A temperature and humidity controlled environmental chamber can be used to validate sensor reliability and performance within product operating specifications. However, this may not simulate the true environment for typical real life product use scenarios and dynamic combinations thereof. Some of the challenges typically experienced includes inducing wear / in-ear versus out of ear state changes, body heat influence and other system operational influences. It is Azoteq's recommendation that practical use of the TWS product in different environments should form part of the functional testing during design validation.

6.6 Noise tests

Normal product noise variation should be evaluated over numerous preproduction units/builds before starting mass production testing in order to gain performance metrics and statistics for establishing the upcoming production limits. An applicable noise failure limit must be considered to reject excessively noisy sensors with presumable quality or assembly issues. Standardised noise tests (whether aimed at radiated and/or conducted noise) as well as other product performance qualifications governed by international standards, should be considered according to the specific underwriting by the IEC body or other known standard body which the product needs to comply with.

7 Interface Description

This chapter provides some high-level information that should be beneficial to a firmware developer who wants to write a driver for one of Azoteq's ICs in a TWS application. The chapter should be read in conjunction with the relevant device's datasheet.

7.1 Host software implementation

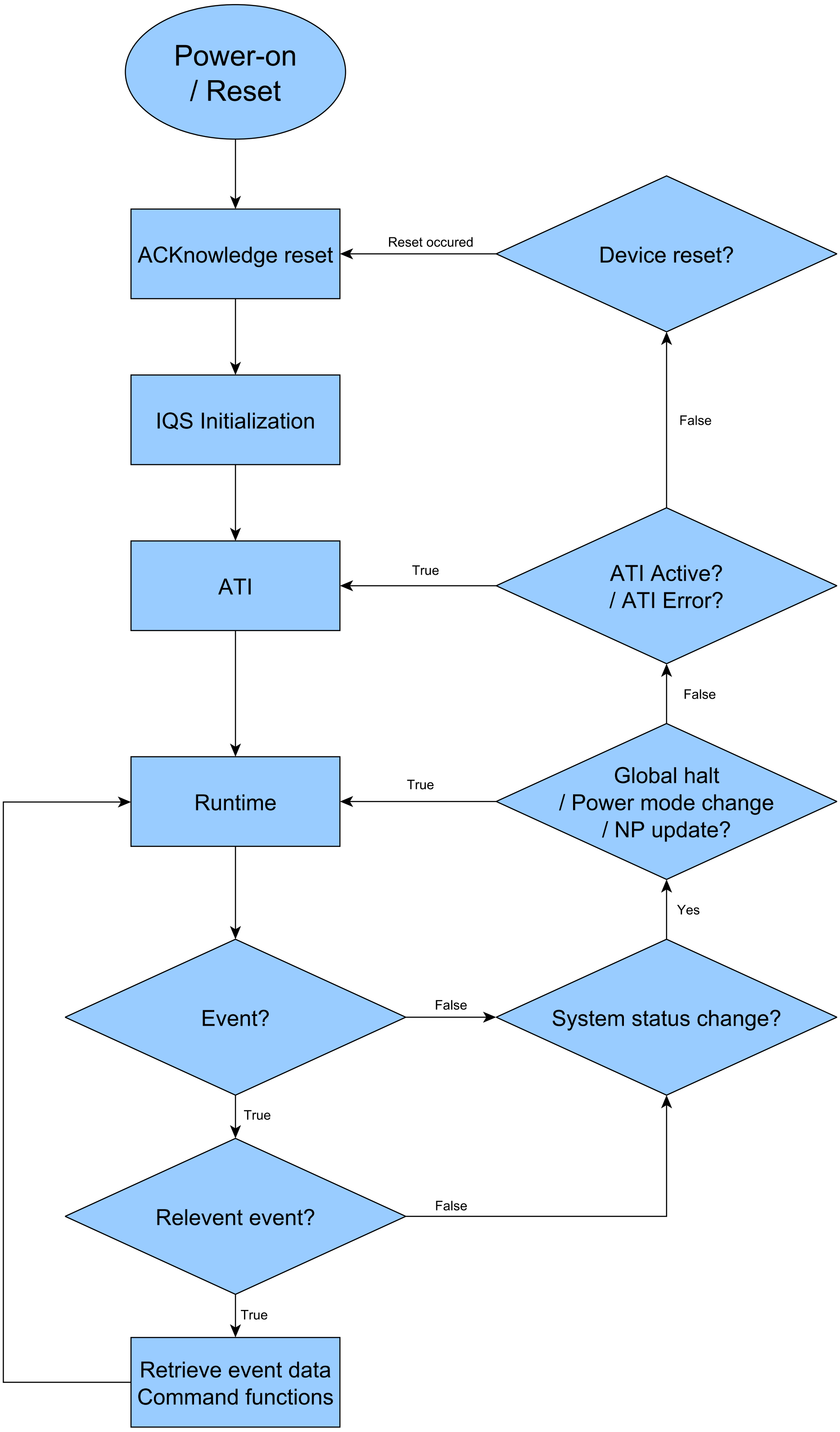


Figure 7.1: Host Software Flow Diagram

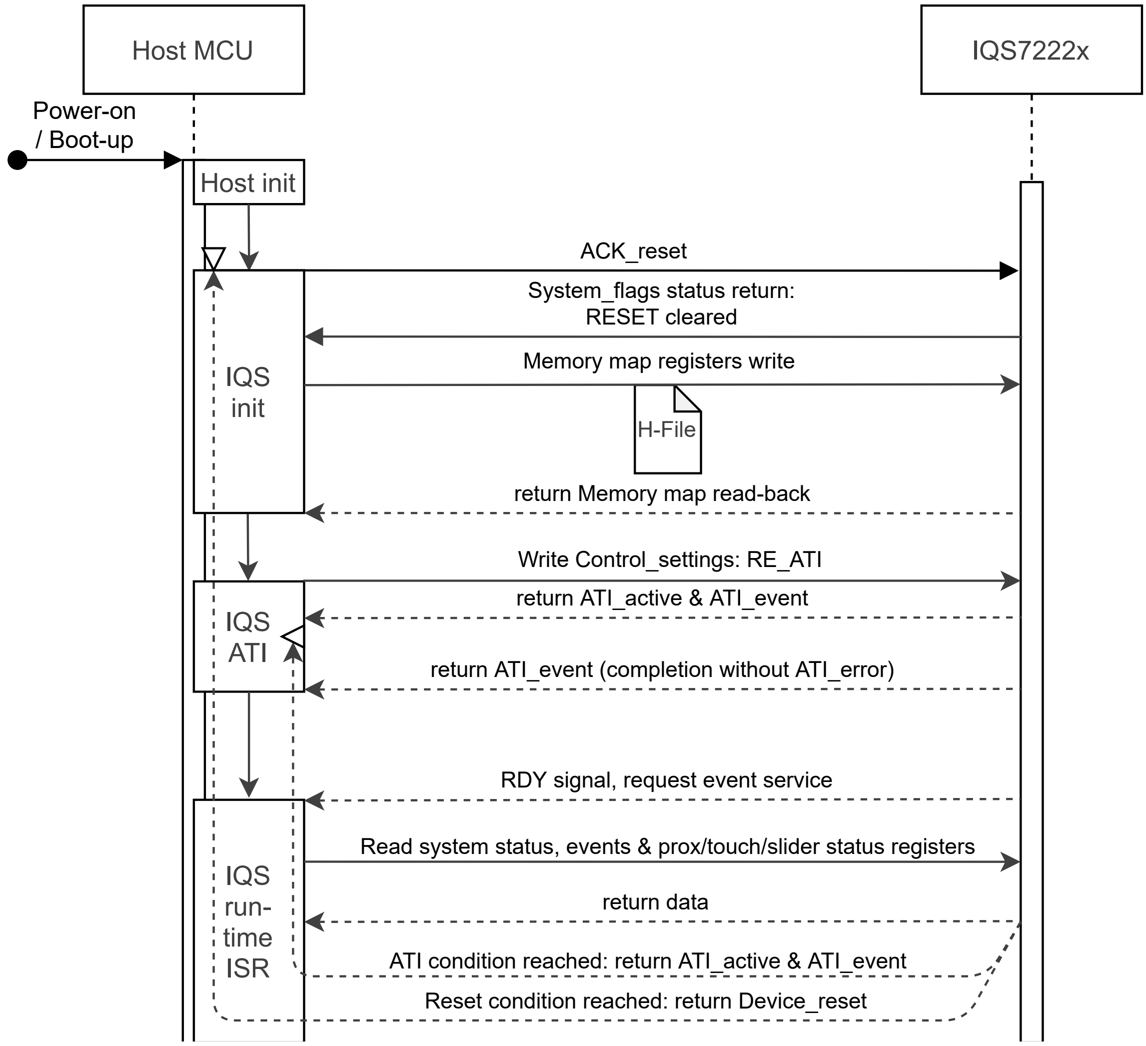


Figure 7.2: Host Software Sequence Diagram

7.1.1 Communication protocol

For examples of I^2C addressing, read, write, force communication requests and other communications related behaviour, please refer to the relevant device's datasheet *I^2C interface* section.

7.1.2 RDY interrupt signal

The RDY (communication ready or interrupt signal) behaviour is important to take notice of and special attention needs to be exercised on devices where RDY and MCLR functionalities are multiplexed on the same pin (like in the case of the IQS323).

7.1.3 Configurable output signal

Most ProxFusion devices (including both IQS7222A and IQS323) offer a configurable GPIO output that can be set up as needed with assignment to a specific event or status flag to signal or control either another ASIC, like a PMU, or specific drivers for loads (LEDs, motors etc.) without necessitating MCU service overhead.

8 Mass Production / Testing

This chapter provides information concerning testing during mass production.

8.1 Production preparation

Hardware should be suitably prepared to allow efficient and acceptable test coverage of sub-assembly and final product assemblies.

- Test point design
  - Placement of all test points (TPs) should be accessible within test needle pitch with sufficient clearance
  - TPs located all on the same side of an FR4 board is preferred as opposed to dual sided probing through complex support surface cavities and mechanical test jigs which need to be sufficiently aligned
  - Test points on FPC need accurate coverlay cut-out and alignment with the appropriate stiffener adhered on the back (for support and to prevent needles from damaging the FPC)
  - Size and shape of test pads should be considered in relation to the test needle, substrate and plating/solder finish

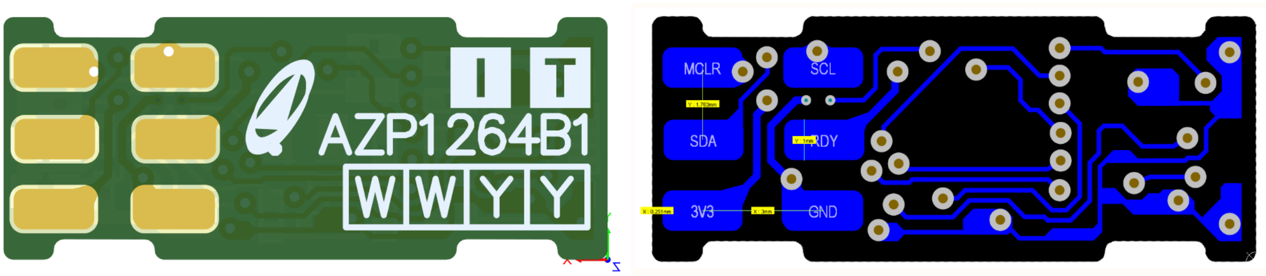


Figure 8.1: Main PCB Test Point Layout

- Test jig and adhesive liner capacitive contributions
  - Consider the contribution of additional capacitive coupling from contact surfaces of test jigs in close proximity or in direct contact with electrode pads
  - It is advised that the parts of a test-jig which is housing the PCBA/FPCBA sub-assembly is manufactured from non-conductive materials such as ABS-plastic or plexi-glass
  - Metal or conductive materials can be used to simulate a typical human interaction for self-capacitive sensors and such conductive plates / stylus / slugs should be grounded / earthed with the system's common ground. The electrodes should remain electrically isolated from such testing fingers through the use of the attached adhesive liners or an attached overlay such as the product's housing

Figure 8.2: Test Jig Non-conductive Carrier

- Automated optical inspection (AOI)
  - Typically used in high-precision SMT pick-and-place post-reflow quality inspection steps
  - Can also be done on bare-PCB/FPCB to replace traditional electrical/flying probe testing
  - AOI is recommended and beneficial for complex, intricate assemblies but not a strict pre-requisite
  - Acceptable test coverage can be obtained by thorough in-circuit and functional test procedures without the need for AOI, but are slower and limited for other quality feature checks

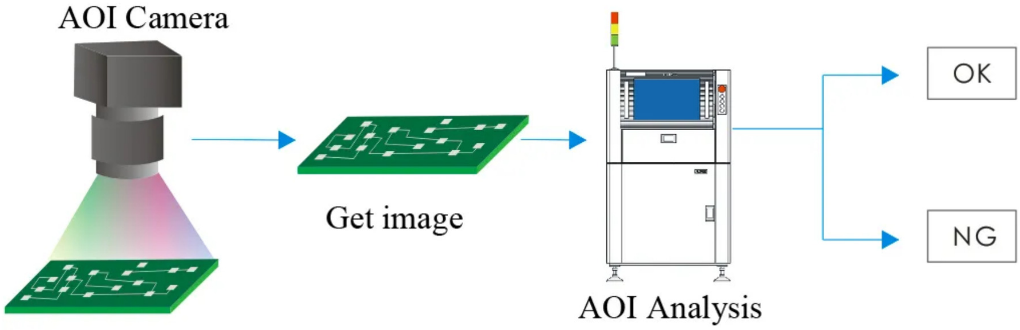


Figure 8.3: Automated Optical Inspection (AOI)

8.1.1 Response vs. current consumption

There exists a trade-off between the responsiveness of a sensor and the average amount of current being consumed to reach a specific response or sampling rate. End-product or UX design may dictate the specification for responsiveness but this ultimately impacts the overall system current consumption. TWS products may have combinations of different sensors and functionalities associated to each, but the IQS device will periodically sample/convert each sensor (channel) at the set rate to maintain uniformity of response for all. Current measurement during production testing should allow for typical normal power mode operation as well as slower low-power mode current measurements to ensure acceptable consumption requirements are met and guarantee the stability of a specific mode without irregular/erratic behaviour such as unexpected wake-up from low-power modes or excessive high currents (short-circuit assembly issues).

Standard SMT production line practises and guidelines should always be followed with respect to IC device and sub-assembly handling, manufacturing, storage and transport to ensure quality, high yield and reliability.

8.2 Production Testing: Best practice

8.2.1 Test parameters

- Version information
  - Check device product number
  - Check device major and minor firmware version info
  - Confirm device communication and clear/acknowledge (*ACK RESET*) flag
- Application settings
  - Written configuration settings can be read back
  - ATI specific parameters are distinct and updated
  - ATI completion reached on all channels without any *ATI error* reported
- Functional testing
  - Procedural exercise of all functionality when sensors are activated (can have a test routine implementation)
  - Induced user activation assessment (signal of known or controlled benchmark for sensitivity and reactivity qualification)
  - Raw signal noise assessment
- Current consumption
  - Average current measurement over long periods is constant for normal device operation
  - The integration time period should be long enough such that starting or ending the measurement midway through an active cycle/conversion does not have a large effect on the measured average current

Preproduction builds of increasing quantities are a general sound practise used to choose applicable tests, gathering test data and establishing limitations thereof. Statistical means, standard deviations and typical outlier criteria may be used to discover and inspect certain units in detail to institute a basis for known risks or critical design aspects which should be evaluated, addressed and improved upon during the preparation leading towards final or mass production.

Completing all test procedures and processing all of the captured data before final product assembly is critical or crucial for general product qualification. Some assembly steps may be costly and irreversible in nature (baking/curing a potting or encapsulated assembly, welding or gluing housings together or sealing for water resistance) which then prevents re-testing of certain parts/exposures after such production stages and may lead to destructive consequences if require reworking.

9 Revision History

Release	Date	Comments
v1.0	2023/03/01	Initial document released

A Bill of Materials

The following Table A.1 provides the bill of material detail for the schematic layout of Figure 5.2.

Table A.1: Bill Of materials

Comment	Description	Designator	Footprint	Manufacturer (P/N)
IQS7222A	IQS7222A-CSP-18N	U1	WLCSP-18N interleaved ball	Azoteq (IQS7222A001CSR)
680 nH	Inductor, ceramic core, wire wound	L1	0603 (1.6 x 1.05 mm)	Wurth (744761268A)
150 pF	Capacitor, ceramic, X7R	C1	0201	Murata (GRM033R71C151KA01)
100 pF	Capacitor, ceramic, X7R	C2, C4, C6, C9	0201	Murata (GRM033R71C101KA01D)
2.2 µF	Capacitor, ceramic, X5R	C3, C5	0201	Panasonic (ECJ-0EB0J225M)
4.7 µF	Capacitor, ceramic, X5R	C3, C5	0402	Samsung (CL05A475MQ5NRNC)
100 nF	Capacitor, ceramic, X5R	C8	0201	Murata (GMD033R60J104KE11D)
100R	Resistor, 100 Ω, 1%, 0.05W	R1, R2, R3, R5, R6, R7	0201	Panasonic (ERJ-1RKD1000C)
300R	Resistor, 300 Ω, 1%, 0.05W	R8	0201	Panasonic (ERJ-U01F3000C))
DNP	Resistor, DNP	R9	0201	
0R	Resistor, 0 Ω	R10	0201	
BM23FR0.8-10DS-0.35V(895)	Header, 10-Way Plug SMT	P1	Special	Hirose (BM23FR0.8-10DS-0.35V(895))
TP1, -2, -3, -4, -5, -6	Test points	1, 2, 3, 4, 5, 6	⌀1 mm exposed Copper pad	PCB
AZP1264B1	FR4-PCB, ENIG finish, 0.4 mm thick, 2-layer	AZP1264B1		PCB manufacturer of choice

B Mechanical Design

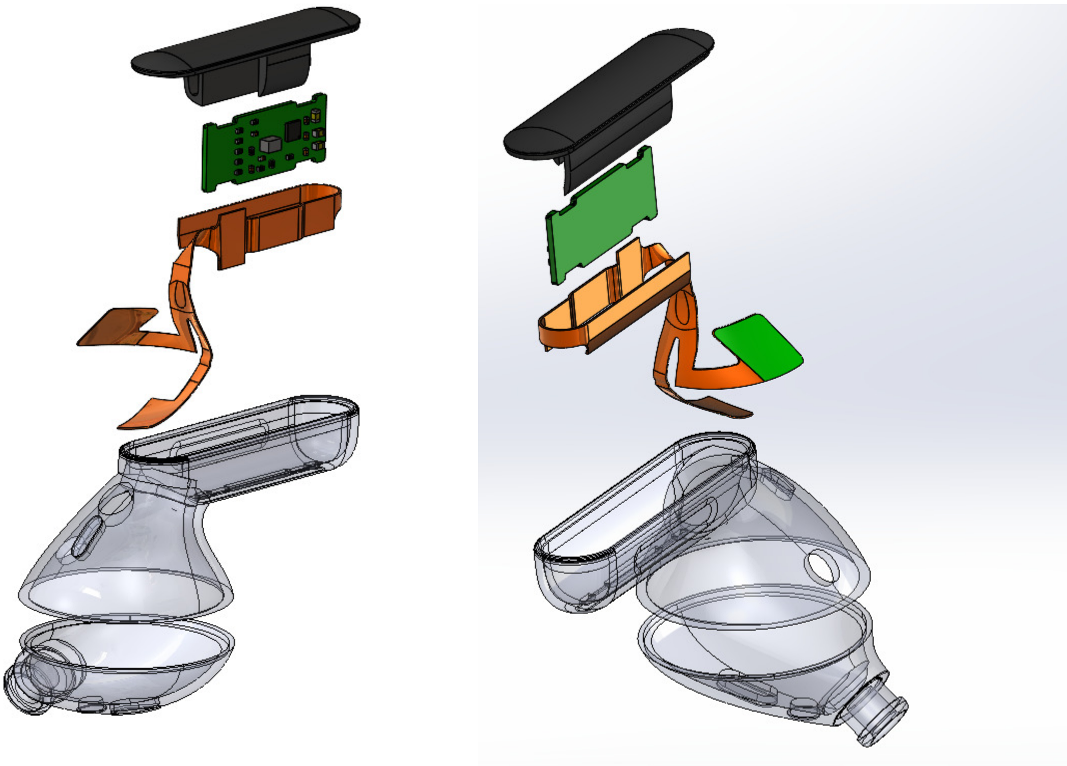


Figure B.1: Stem TWS exploded assembly

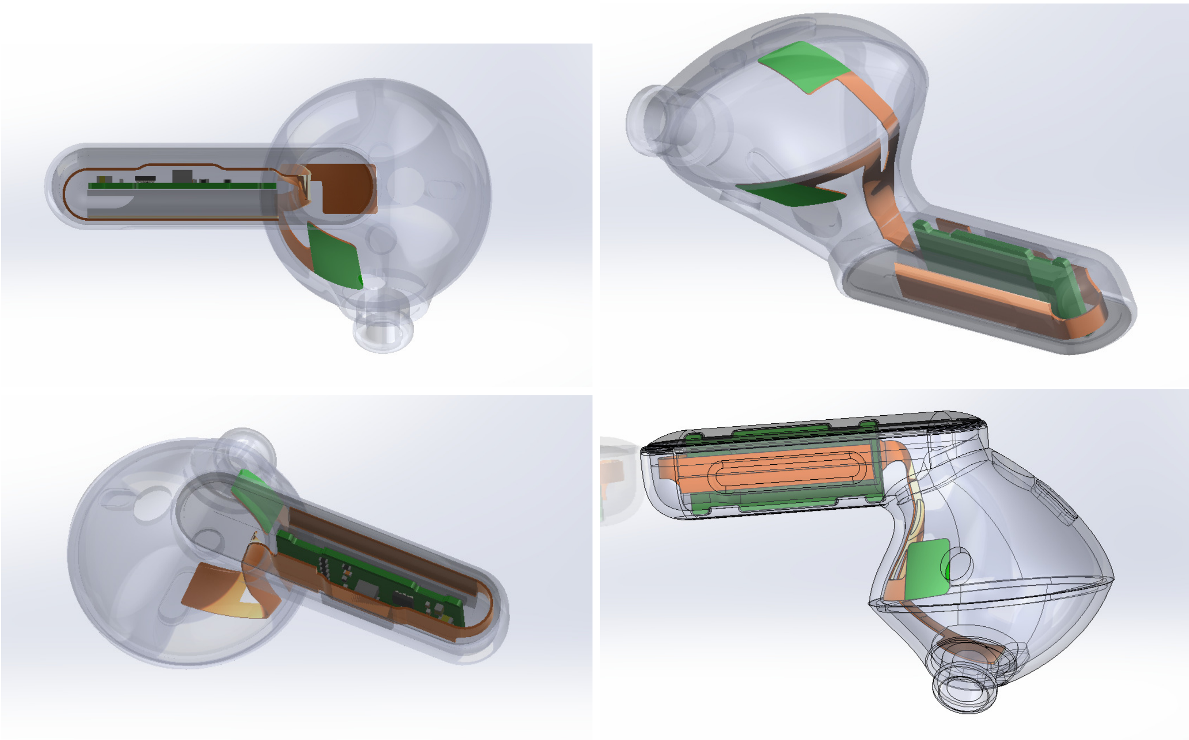


Figure B.2: Stem TWS final assembly

C Glossary

Abbreviation	Term	Definition
ABS	Acrylonitrile butadiene styrene	A common thermo plastic polymer typically used in electronic housing material
ANC	Active Noise cancellation	A method for reducing unwanted sound by the addition of a second sound specifically designed to cancel the first
AOI	Automated Optical Inspection	An automated visual inspection of printed circuit board (PCB) (or assembly) manufacture where a camera autonomously scans the device under test for both catastrophic failure (e.g. missing component) and quality defects (e.g. fillet size or shape or component skew)
ASIC	Application-specific Integrated Circuit	Integrated circuit for a particular use
BLE	Bluetooth Low Energy	A wireless personal area network technology standard for mobile electronics
CH	Channel	A software defined instance of a single sensor with related settings, measurement values and UI processing
CPU	Central Processing Unit	Main processing circuitry for arithmetic, logic, control and input / output operations
CS	Count(s)	A single unit / quantity of an arbitrary amount of charge or current measured by the ProxFusion sensor engine
	Cycle	A period during which selected sensors are sampled. One measurement is taken per ProxFusion measurement circuit.
FPCB	Flexible Printed Circuit Board	A technology for assembling electronic circuits by mounting electronic devices on flexible plastic substrates, such as polyimide or transparent conductive polyester film
IC	Integrated Circuit	A set of electronic circuits on one small flat piece (or "chip") of semiconductor material, usually silicon
I^2C	Inter-Integrated Circuit	A synchronous, multi-controller/multi-target (master/slave), packet switched, single-ended, serial communication bus
IRQ	Interrupt Request	A hardware signal sent to the processor that temporarily stops a running program and allows a special program, an interrupt handler or interrupt service routine, to run instead
ISR	Interrupt Service Routine	A special block of code associated with a specific interrupt condition
LED	Light-Emitting Diode	A semiconductor device that emits light when current flows through it
LTA	Long Term Average	A slow filtered response or averaged value evaluated over a long term period and used as a baseline or reference to differentiate instantaneous or sudden changes in new measurement data
MCU	Microcontroller Unit	A small computing device with processor core(s), memory, peripherals and basic input / output functionalities
PCB	Printed Circuit Board	A non-conductive material with conductive lines printed or etched. Electronic components are mounted on the board and the traces connect the components together to form a working circuit or assembly
PMU	Power Management Unit	A microcontroller that governs power functions of digital platforms
SoC	System on Chip	An integrated circuit that integrates most or all components of a computer or other electronic system including graphics processing units and / or radio's with communication modems
TWS	True Wireless Stereo	A audio product using Bluetooth signals instead of wires or cables to transfer sound. TWS differs from wireless accessories that do not physically connect to a media source but still rely on physical connections to ensure that multiple parts of a device can function together.
UI	User Interface	The space where interactions between humans and machines occur
USB	Universal Serial Bus	An industry standard that establishes specifications for cables, connectors and protocols for connection, communication and power supply (interfacing) between computers, peripherals and other computers.
UX	User Experience	A person's behaviours, attitudes, and emotions about using a product, system, or service

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