PRODUCT DEVELOPMENT

PERSPECTIVES FROM A DESIGN ENGINEER

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04.27.23

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Introduction

23 years of product development experience

- Bose (18 years)
- Motorola (5 years)
- Pratt & Whitney (3 summers)

Electrical, Acoustical, Project Leadership, and Management roles

BSEE University of Miami, Audio Engineering Program

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A Few Product Examples

Banded Headphones

In Ear Headphones

Mobile Phone Handsets

And this one too...

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Product Development

Expectation

Progress

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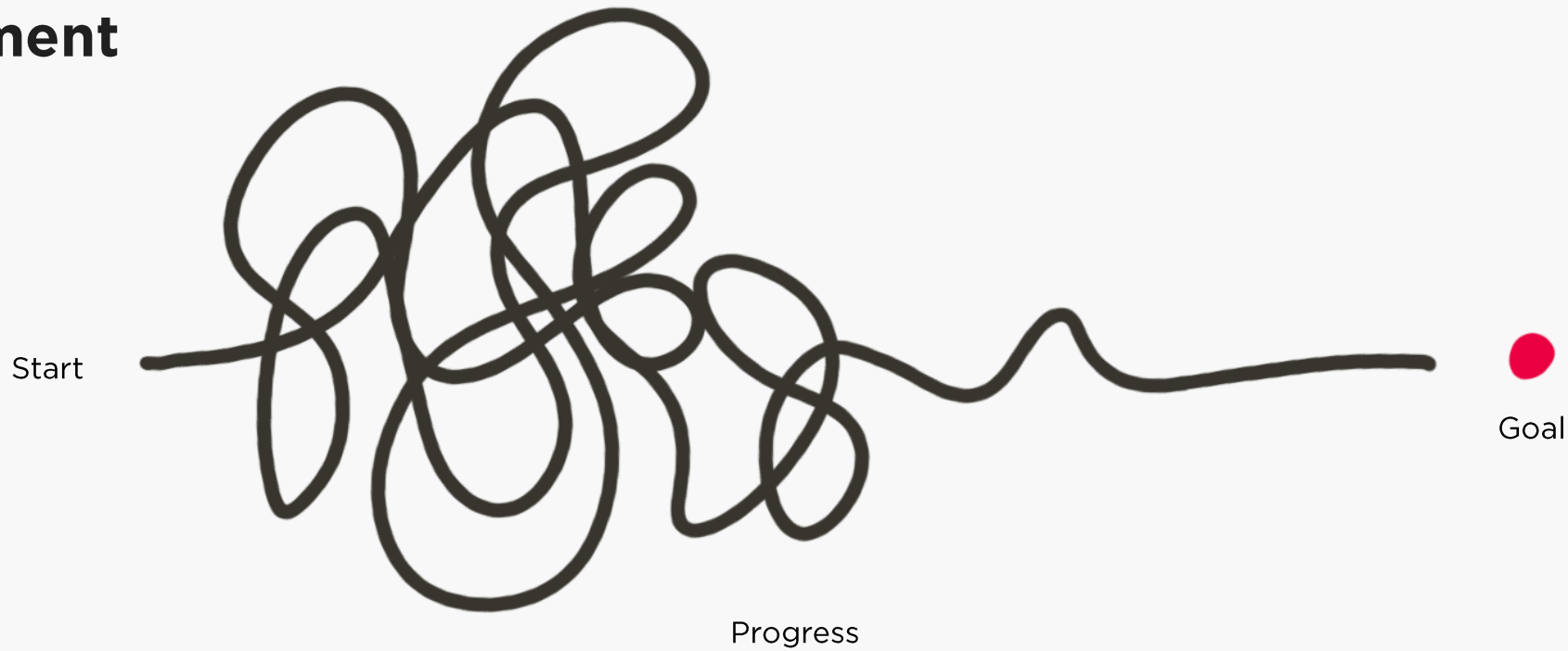
Product Development

Reality



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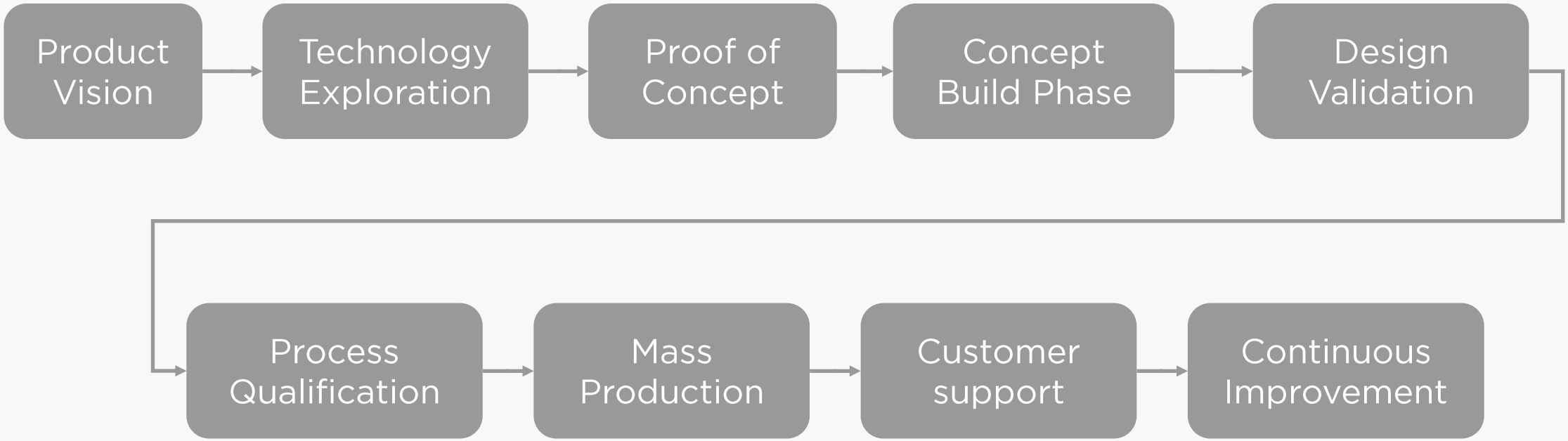
Basic Development Process



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Product Definition

01 | Product Mission
Primary use case. What is the purpose for this product to exist? What problem is it trying to address for the customer?

02 | Key Differentiators
Required features and functions to realize product vision. These distinguish this product from competitive set.

03 | Core Functionality
Basic functions that must be included, but do not differentiate the product

04 | Other Desirable Features
Wanted, but willing to sacrifice if necessary

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Product Requirements

01 | Functional
Design fundamentals, key functions, performance drivers.

02 | User Experience
How the customer will interact with the product. Includes user interface, physical features.

03 | Manufacturability
Materials, process, factory capabilities, supply chain considerations

04 | Reliability
Define use profile, expected product life.

05 | Regulatory
Legal requirements, necessary certifications, safety.

06 | Business Case
Project cost, unit cost, projected sales volumes, delivery costs, market value

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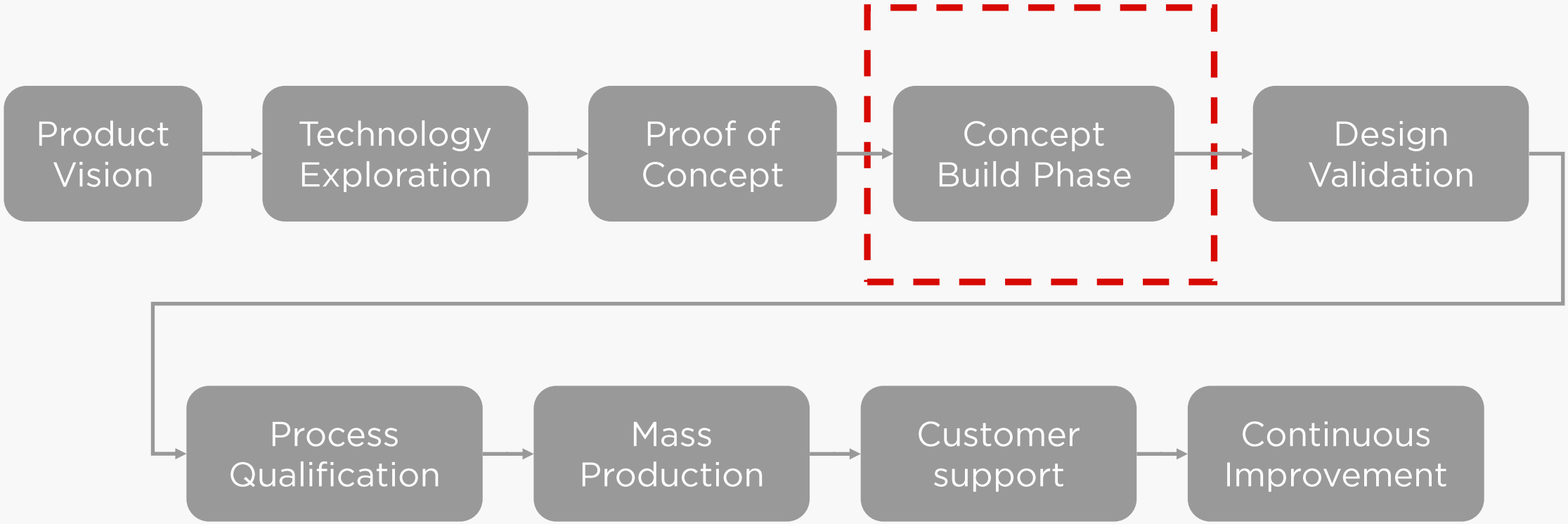
Basic Development Process



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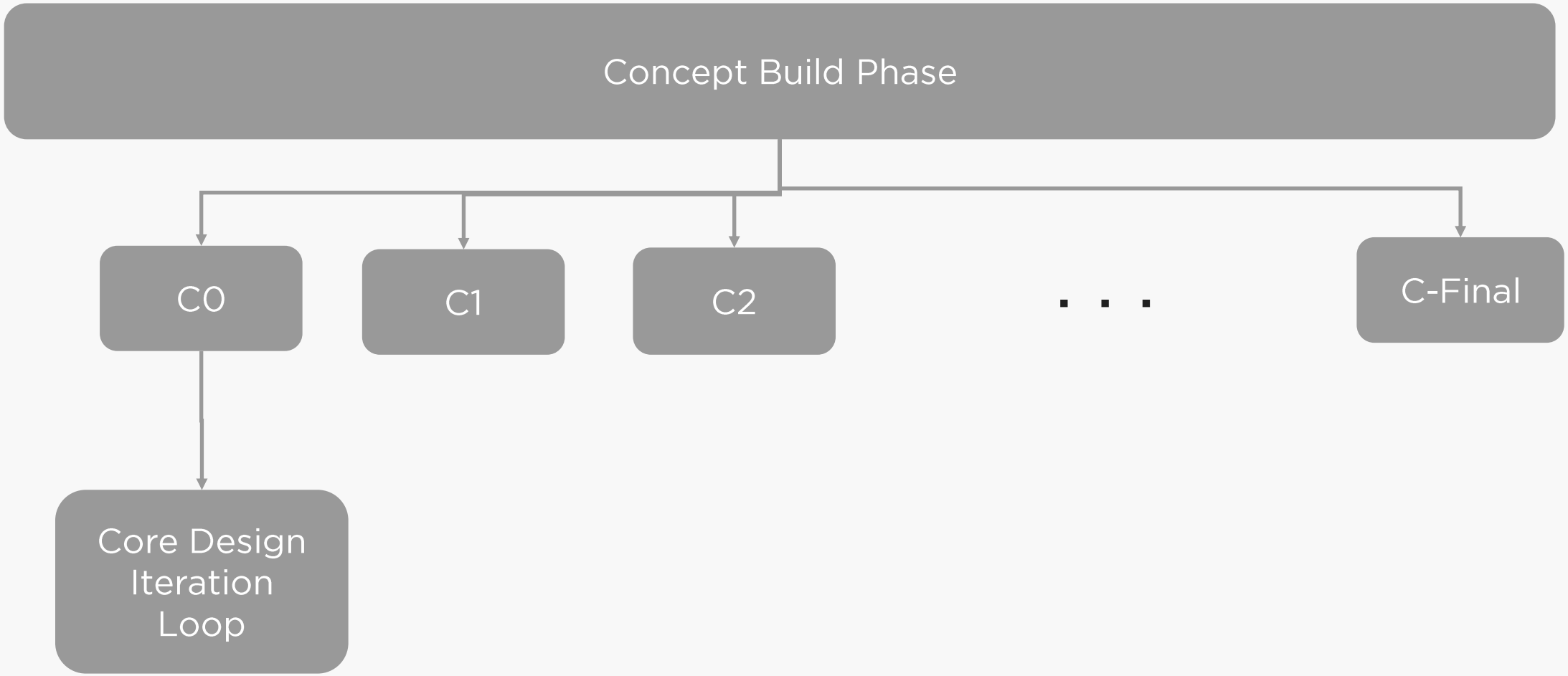
Concept Build Phase – Detail



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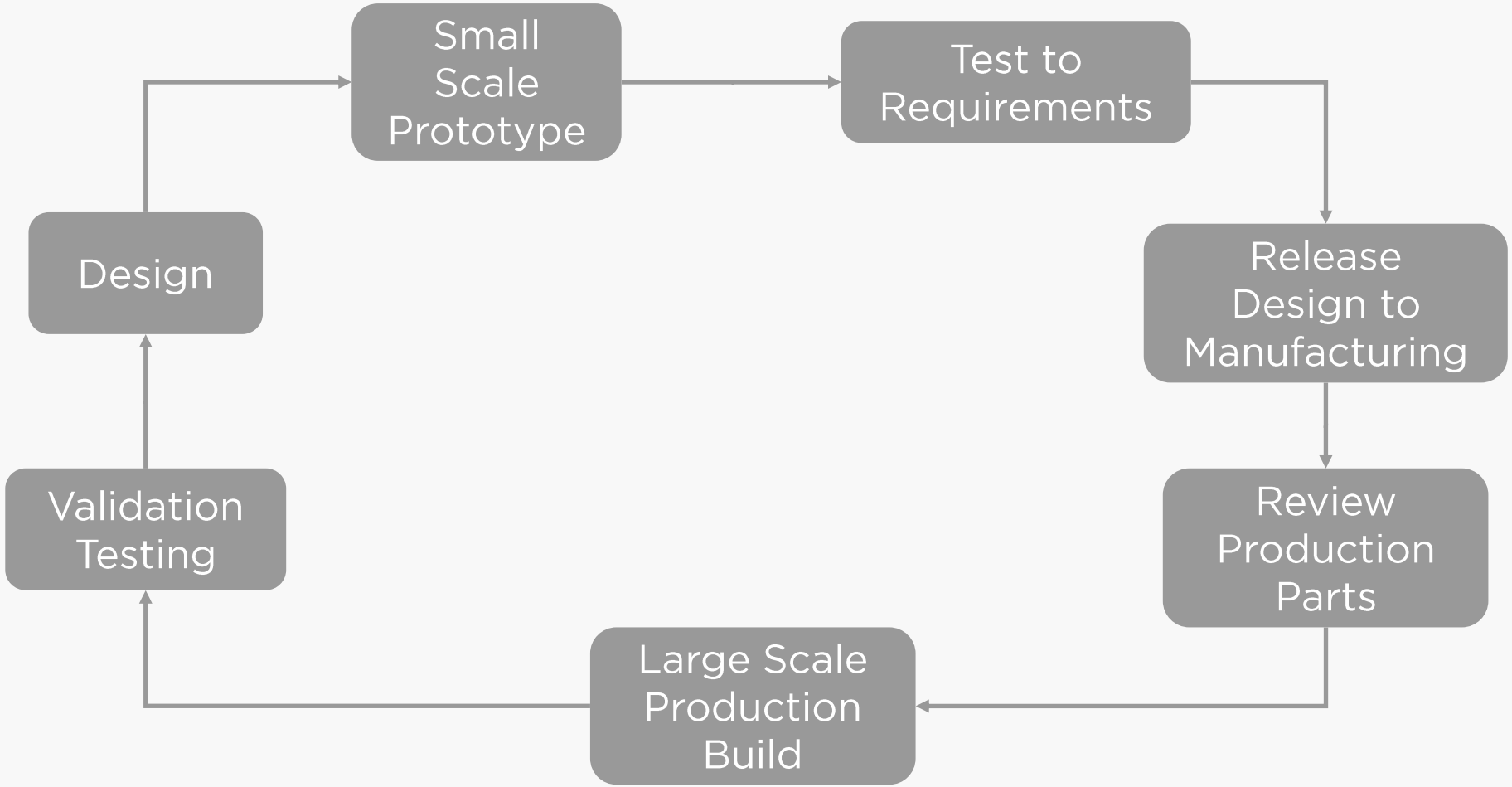
Concept Build Phase – Core Design Iteration Loop



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Creating a Schedule

Planning development activities

- Break work down into actionable tasks
- Understanding time required for each

Anticipating risks and likely problems

Defining maturity milestones

Allowing contingency time for discovered work

- Known unknowns

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PROTOTYPING A COMPLEX SYSTEM

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Protyping – Increasing Complexity

01 | Targeted Breadboard
Simplified prototype designed to answer a specific question

02 | Full System Mockup
First crack at a full, usable system. Basic functionality. Not user friendly.

03 | Fully Integrated Prototype
Form factor integration of all components. Some allowances for test interface remain. Product is generally usable but may not be feature complete.

04 | Final Product
Fully realized product, with full functionality. Intended user experience.

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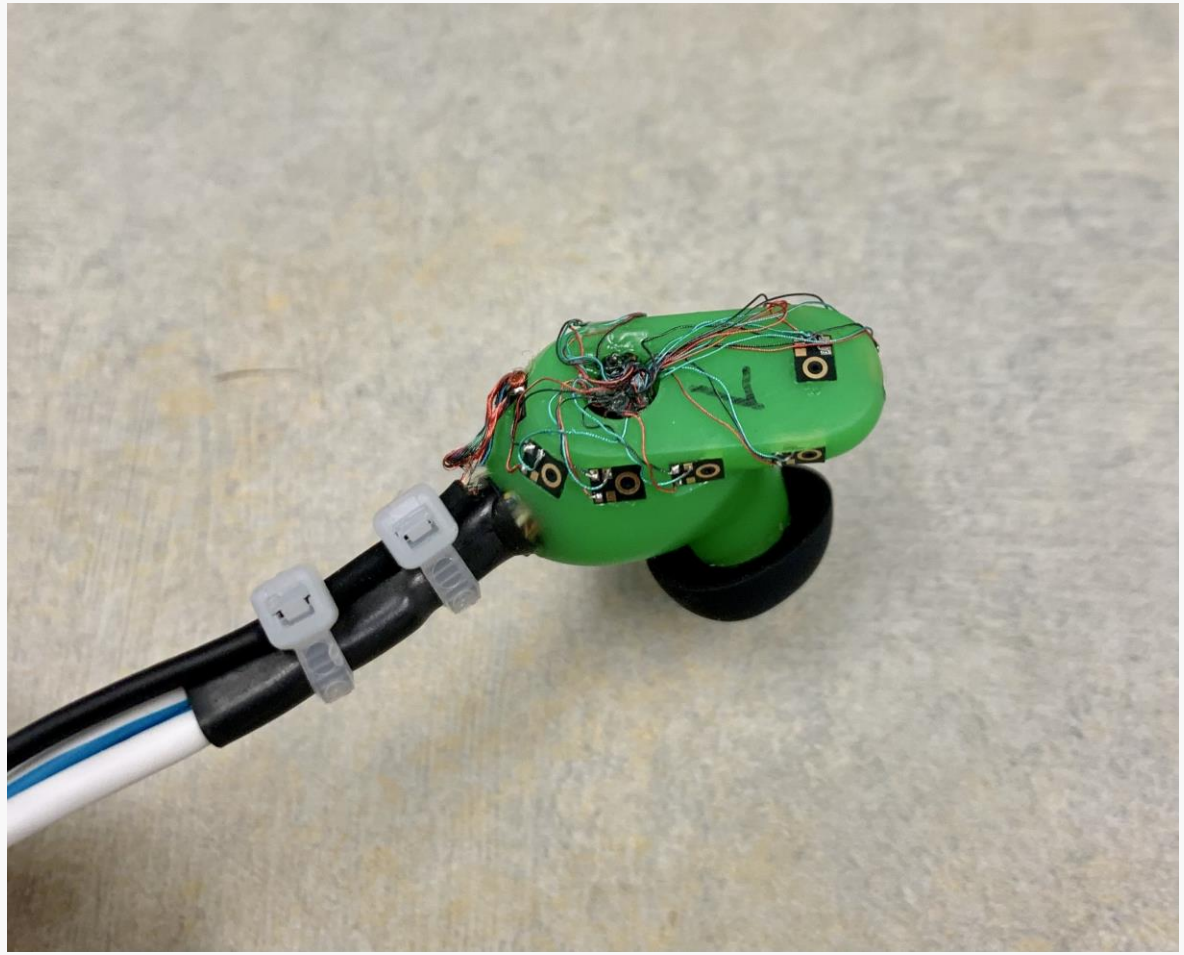
QC Earbuds II Example

01 | Targeted Breadboard

Simplified prototype designed to answer a specific question

Ex: Where should we put the microphones? How many should we use?



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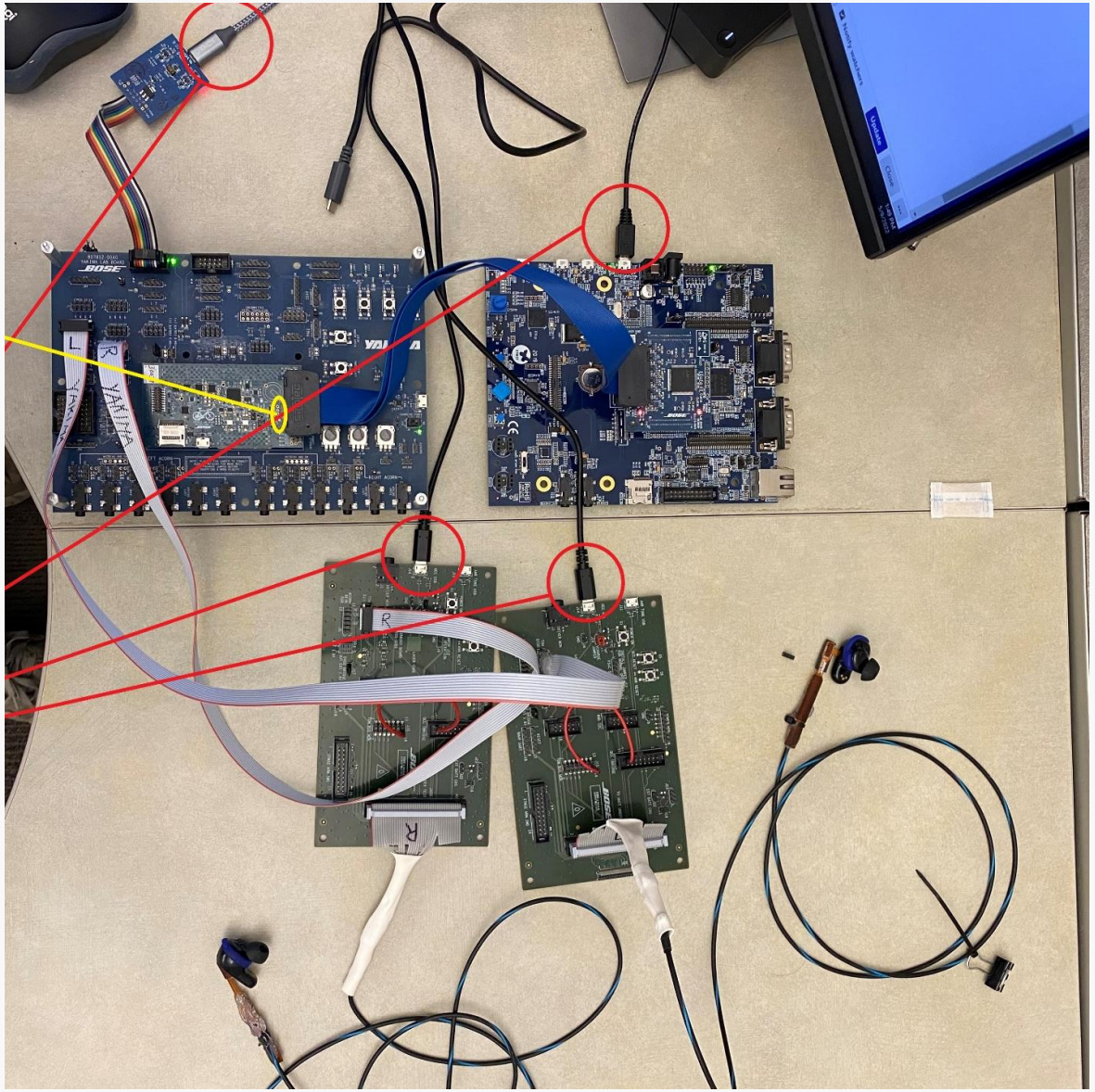
QC Earbuds II Example

02 | Full System Mockup

First crack at a full, usable system. Prototype parts. Basic functionality. Not user friendly.



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QC Earbuds II Example

03 | Fully Integrated Prototype

Form factor integration of all components. Mix of some prototype and some manufactured parts. Some allowances for test interface remain. Product is generally usable but may not be feature complete.

FW functionality is maturing.

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QC Earbuds II Example

04 | Final Product

Fully realized product, with full functionality. Production parts and assembly processes. Intended user experience.

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UNEXPECTED DEVELOPMENT CHALLENGES

REAL WORLD EXAMPLES

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OE1 Headphones

Product Overview

Wired, passive audio playback headphone

New on-ear form factor and acoustic design

Decided to use a new supplier for acoustic mesh

New manufacturing partner building the product

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OE1 Headphones

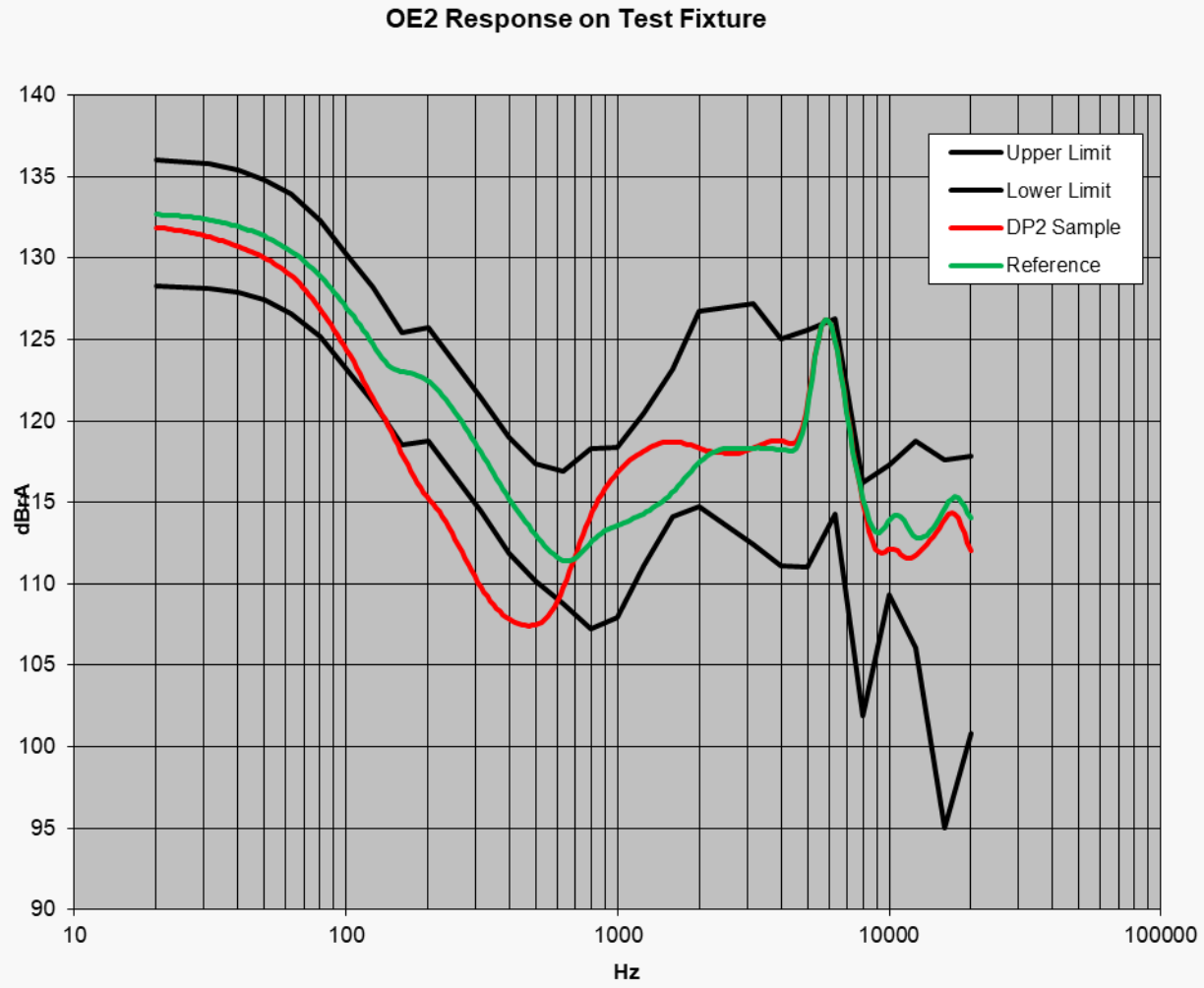
Build 1 - Acoustic Response Issue

First build at factory

Acoustic output not meeting expectation

Root caused to port impedance – too high, caused by acoustic mesh resistance out of spec

Decision: Provide qualified mesh material with known characteristics from known supplier for next build



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Acoustic Mesh – OE1 Headphones

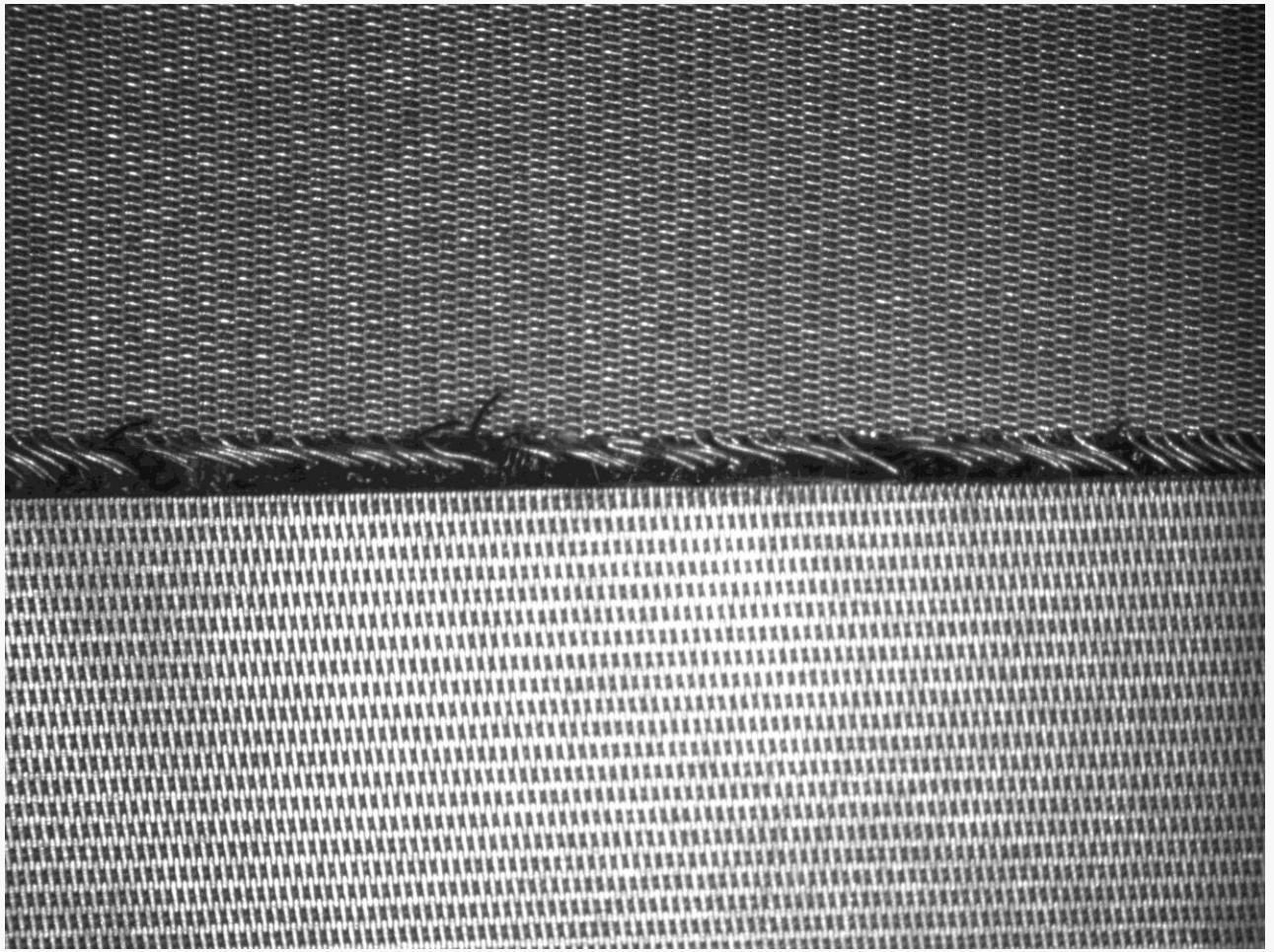
Build 2 - The Problem Persists

Bose tested and shipped new material

At the following build: problem recurred

Mesh appeared to be visually different than what was supplied

Bose Supplied Material



Material at Build

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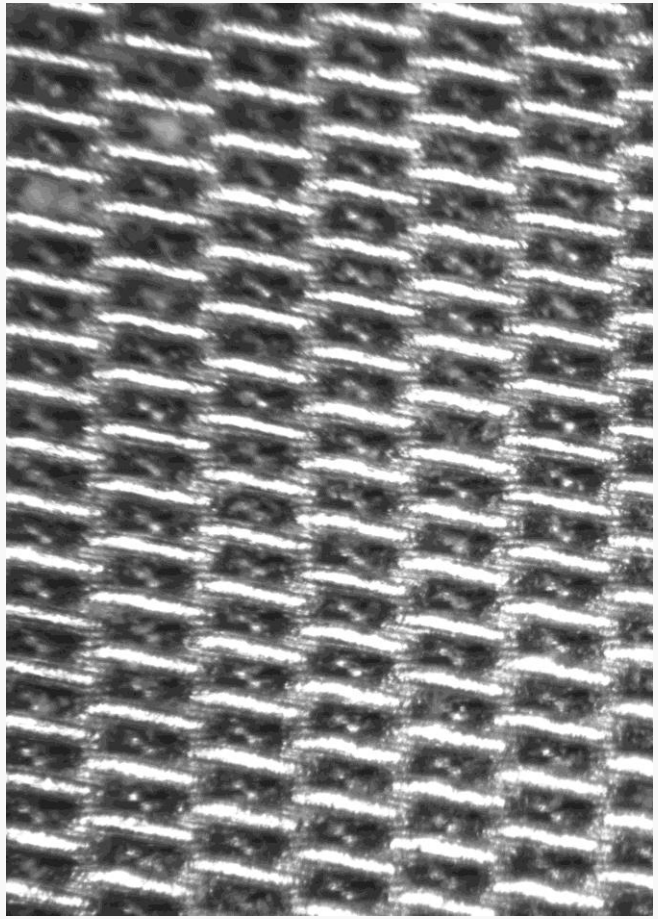
Acoustic Mesh – OE1 Headphones

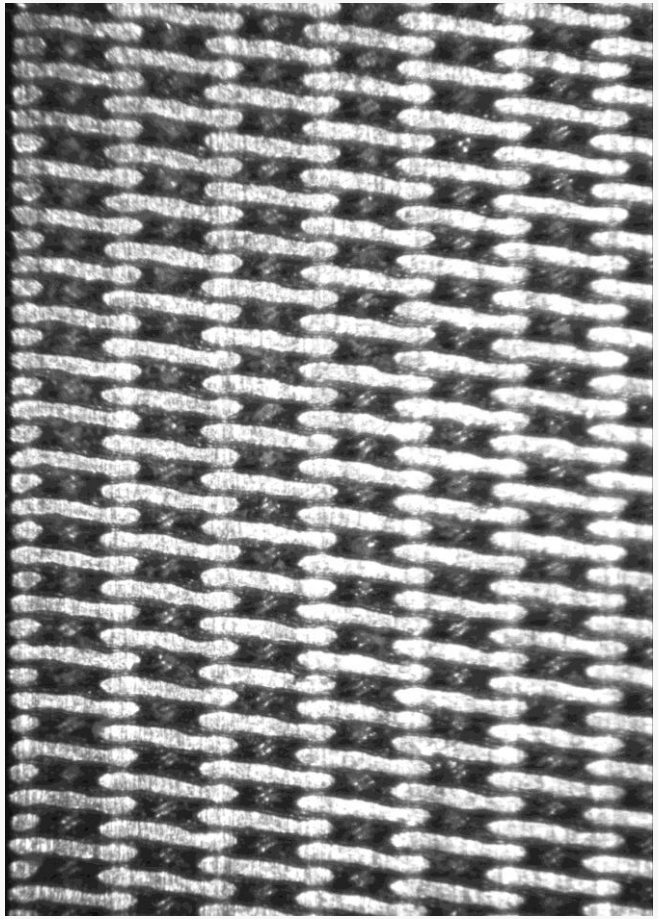
Analysis

Look at mesh under microscope

Wire weave patterns appear similar, but material clearly has been modified



Bose Supplied Material



Material at Build

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Acoustic Mesh – OE1 Headphones

Further Investigation

Decided to visit the wire mesh cutting factory

Confirmed: mesh used was indeed Bose supplied material

So what happened??

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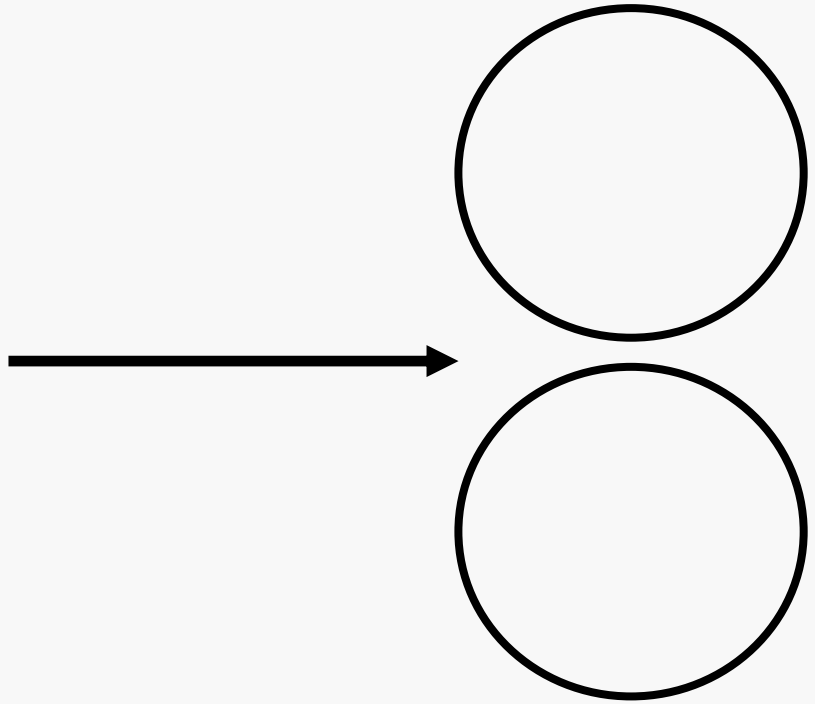
Acoustic Mesh – OE1 Headphones

Finding

Mesh cutting vendor was crushing the mesh between metal rollers prior to cutting

This was to improve the cosmetics of the cut edges

No awareness of the acoustical function of the part



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Acoustic Mesh – OE1 Headphones

Outcome

Eliminated crushing operation on mesh

Since all Bose supplied material was already crushed, we decided to use the locally supplied alternative material which was immediately available in raw form

This was the mesh we had decided to use in the first place!

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IE1 Headphones

Product Overview

Wired, passive audio playback headset

First in-ear headphone developed at Bose

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IE1 Headphones

Problem

IE1 included a passive EQ circuit to adjust the audio response of the headset to match a target.

Observation: Audio performance with some music players was poor.

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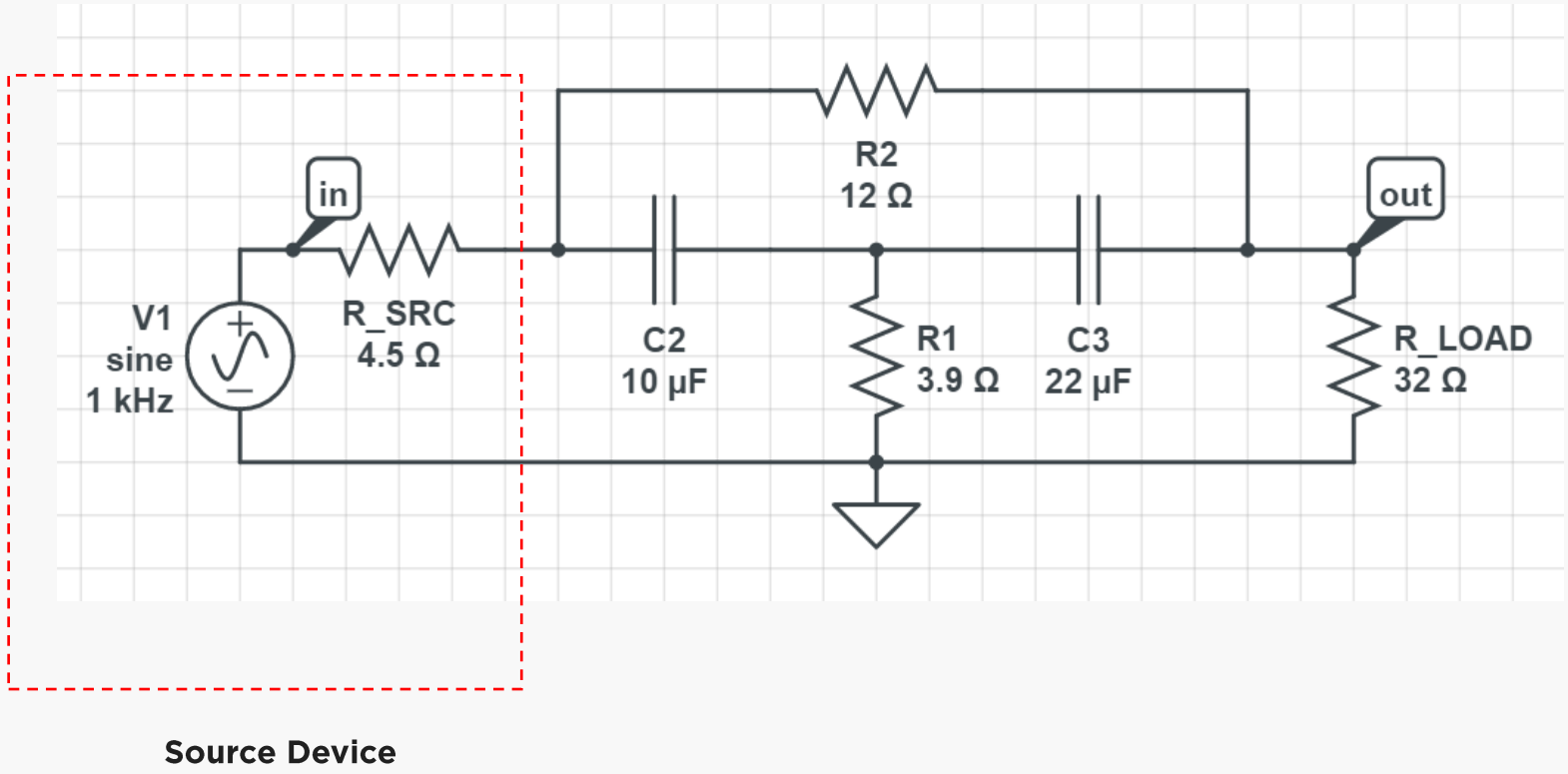
IE1 Headphones - Audio Performance Variation

Problem

Circuit design made assumptions about the electrical characteristics of the audio source device



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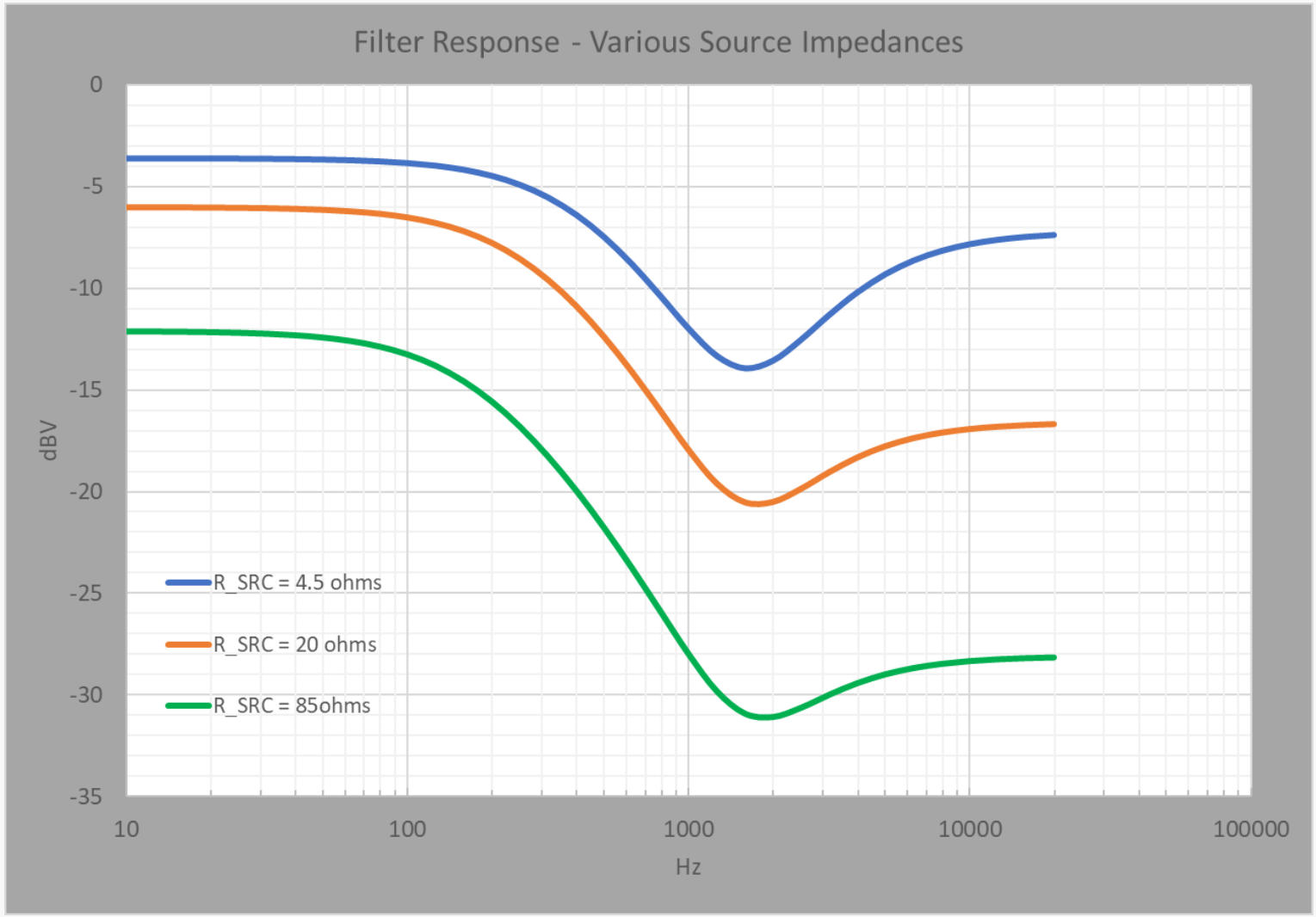
IE1 Headphones - Audio Performance Variation

Problem

Most portable players had an internal source impedance of about 4.5 ohms.

But devices varied considerably. Upon completing a survey of a wide variety of players, some were as high as 85 ohms!

This had significant impact on both output volume as well as EQ shape



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IE1 Headphones - Audio Performance Variation

Outcome

Possible solutions included modified filter circuit (increased cost, physical size) or modifications to physical acoustics (long lead time, expensive to re-tool parts)

Decision not to make any design changes

Requirements placed clear focus on use with most common portable players

Defer improvements to circuit topology, acoustic architecture to future products

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IE2 Headphones

Product Overview

2nd generation of wired, passive in-ear headphones

Included a new passive EQ circuit immune to source impedance induced variation

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IE2 Headphones

A Shocking Problem

During user testing of development units, participants reported sensation of electrical shocks to their ears while plugging headset into a treadmill and running.

Root cause: static buildup dissipating from ear to ground through the earbud itself (plugged into ground via treadmill).

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ESD On Treadmill – IE2 Headphones

Does This Need to be Fixed?

No regulatory concerns

No requirement in product definition specific to this use case

But… customer experience impact was judged to be meaningful

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ESD On Treadmill – IE2 Headphones

Outcome

Problem should be corrected

Changed plastic resin to include metal powder content

This reduced the impedance of skin contact with the bud housing, allowing the ESD to discharge unnoticeably at a lower voltage.

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QC20 Headphones

Product Overview

Wired, in-ear headphone with noise cancellation

Utilizes both Feedback and Feedforward systems for noise reducion

Bose’s first product of this type

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QC20 Headphones – “Tic” Sound

Audible Artifact with Overpressure

Noticed late in program

Audible “tic” sound could be heard under certain conditions in some units

- Noticeable with high impulse, low frequency stimuli
- Noticeable when putting the buds into your ears while powered on, pushing on buds in ears
- Did not occur when unpowered

Small percentage of units exhibited behavior, so few samples to analyze (~3 units)

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QC20 Headphones - “Tic” Sound

Troubleshooting Process

Prioritize nondestructive testing first

Check design for clearance in front acoustic volume, including driver max excursion and mechanical stack up tolerances

Measure electrical output at driver during event

Drive driver with high system voltage, measure response at feedback microphone

Tear down analysis, recognizing risk of losing evidence

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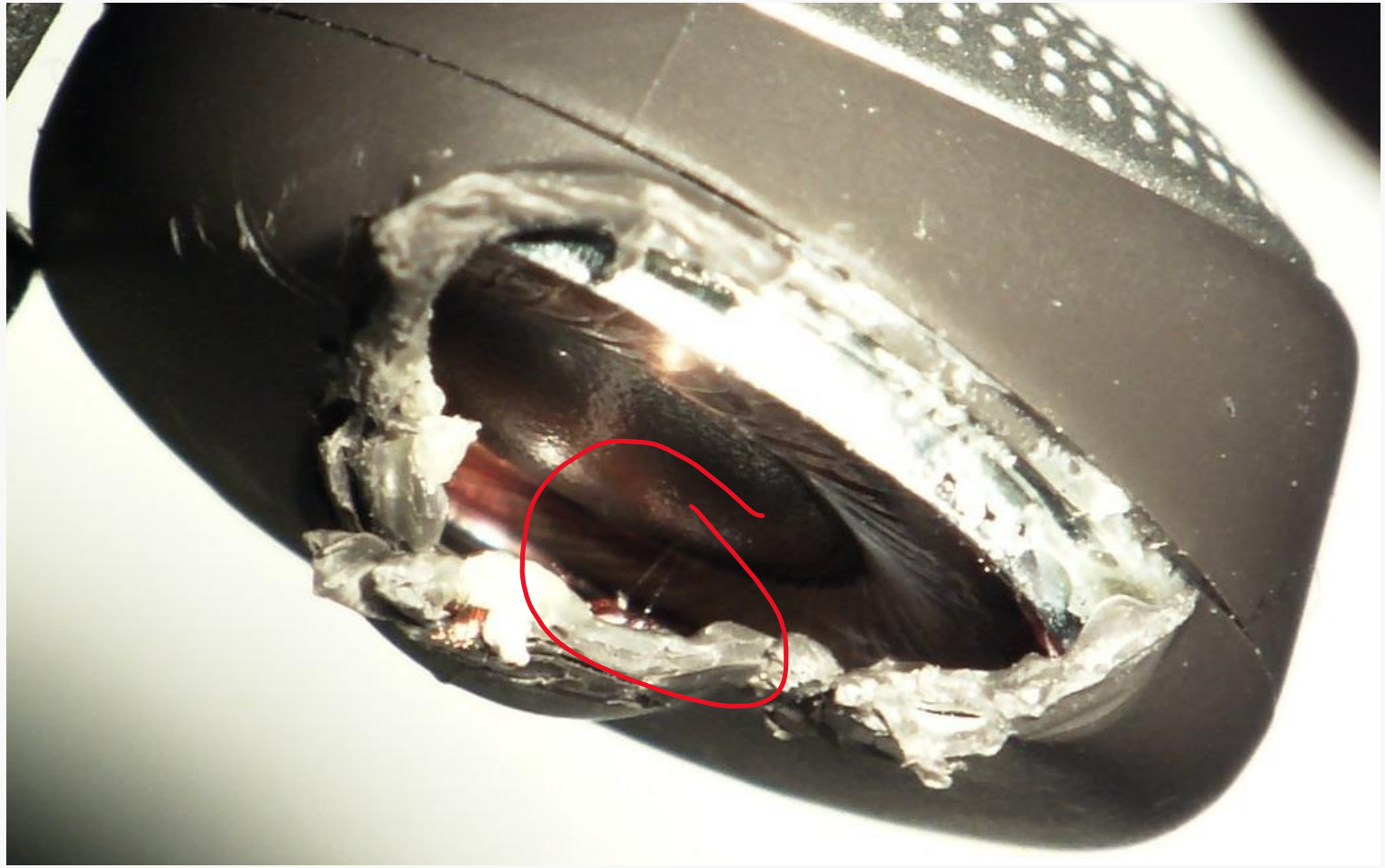
QC20 Headphones - “Tic” Sound

Finding 1

Glue strands from feedback microphone in front acoustic volume could be contacted by driver



Bud nozzle cut away to expose inside of assembly

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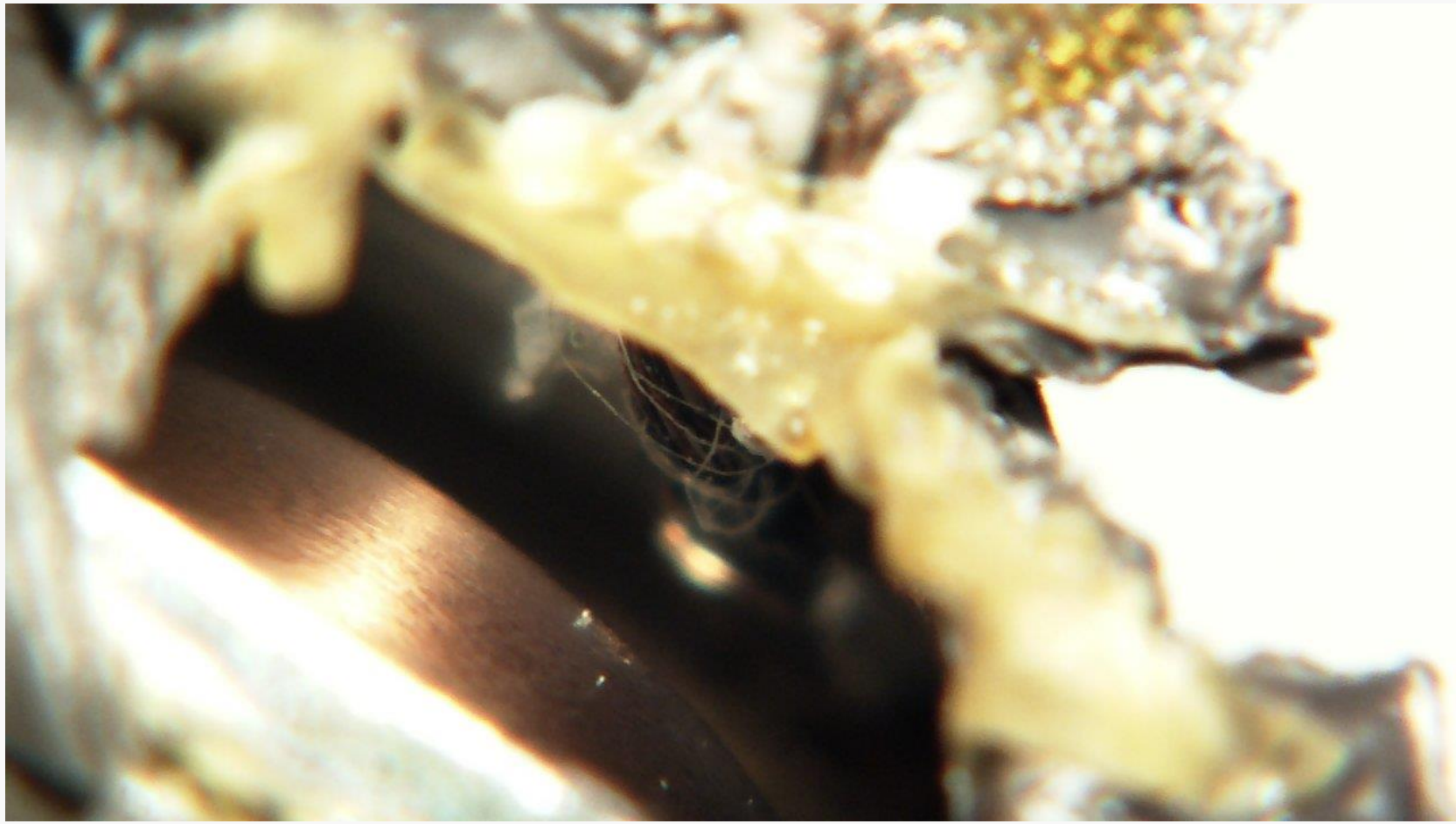
QC20 Headphones - “Tic” Sound

Finding 2

Loose fibers from mic wire bundle inside front acoustic volume could contact driver



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QC20 Headphones - “Tic” Sound

Video

600mV @ 8Hz

Driver diaphragm hits fiber strands

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QC20 Headphones - “Tic” Sound

Solution

Assembly process improvements introduced to prevent these problems

Develop and introduce “Tic test” to production line to detect problem units and prevent escapes

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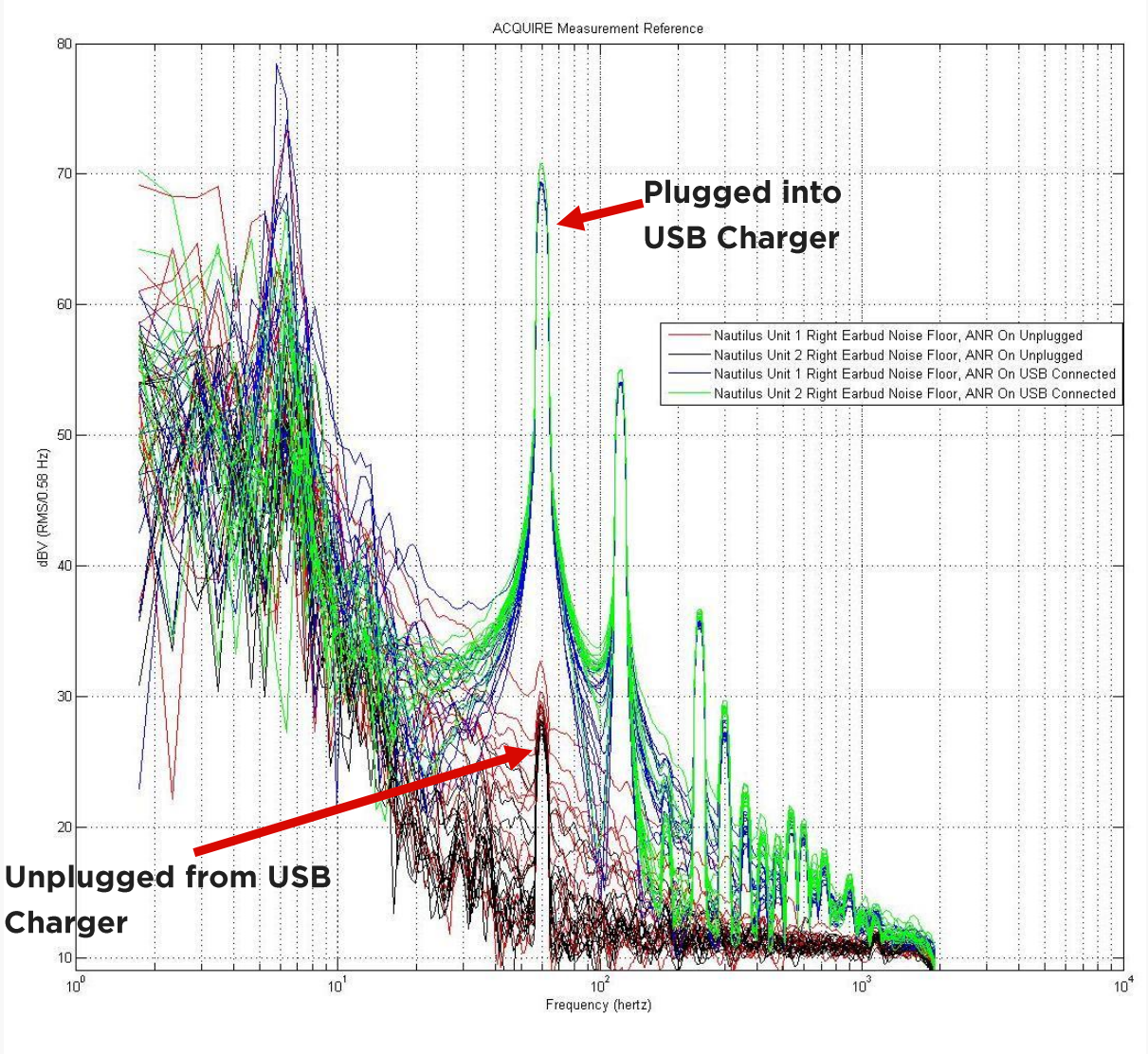
QC20 Headphones – 60Hz Hum

Problem

Headset had audible hum under specific set of operating conditions:

- plugged into a source device that was plugged into wall power (ie a laptop, or smartphone plugged in to charge)
- Source device had a 2 prong plug (ungrounded)
- Headset was plugged into USB for charging
- Device is powered on

Hum was reasonably loud and obviously noticeable



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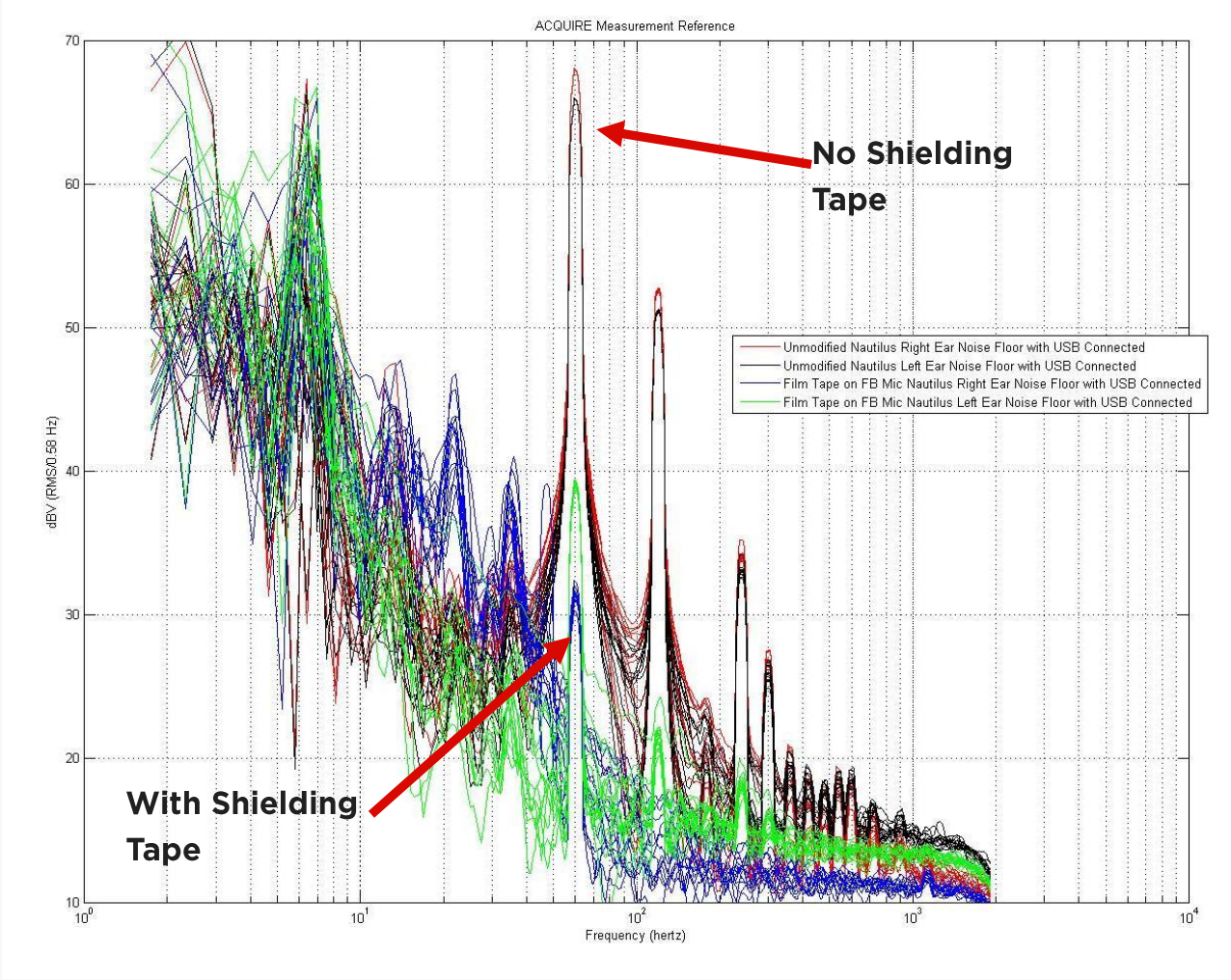
QC20 Headphones – 60Hz Hum

Analysis

Microphone path was suspect due to being a high gain part of system

Disconnecting microphones eliminated the noise pickup



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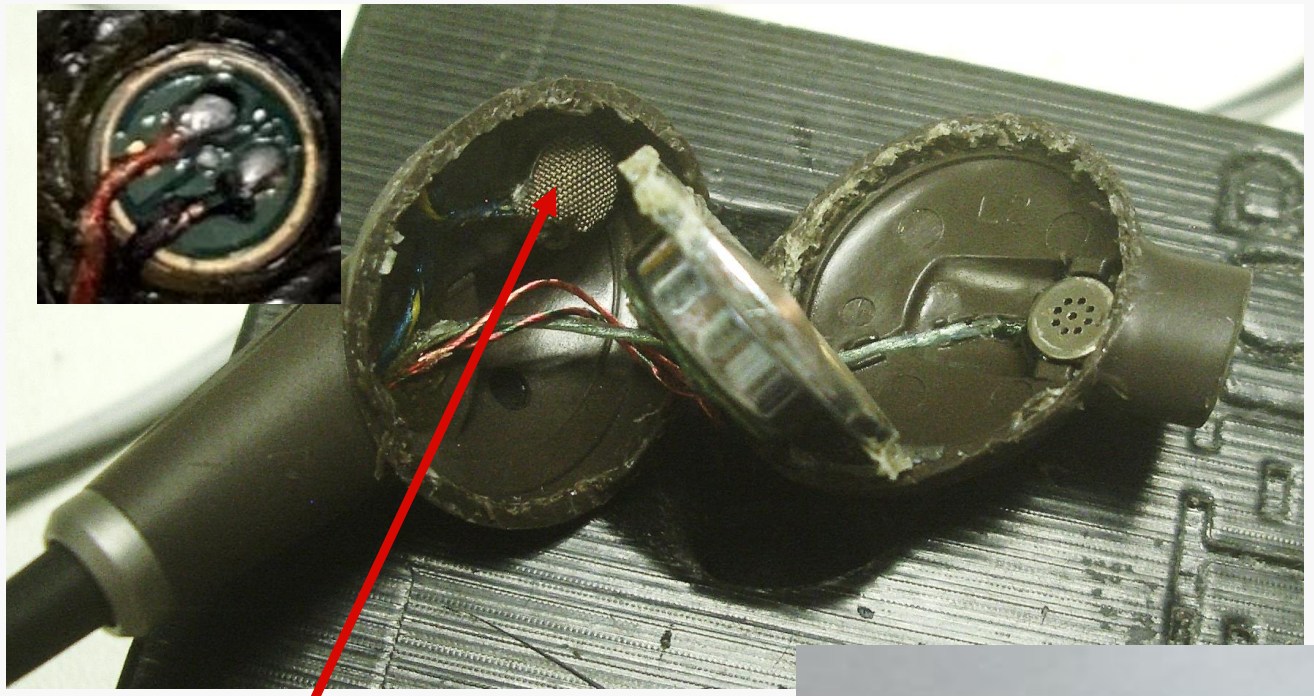
QC20 Headphones – 60Hz Hum

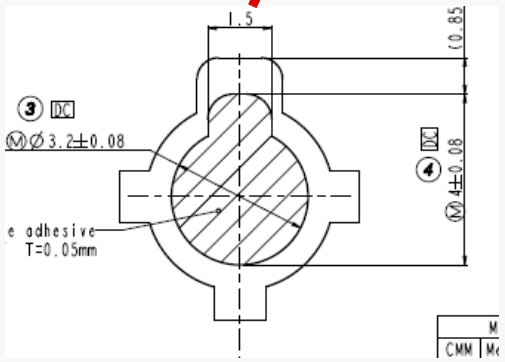
Solution

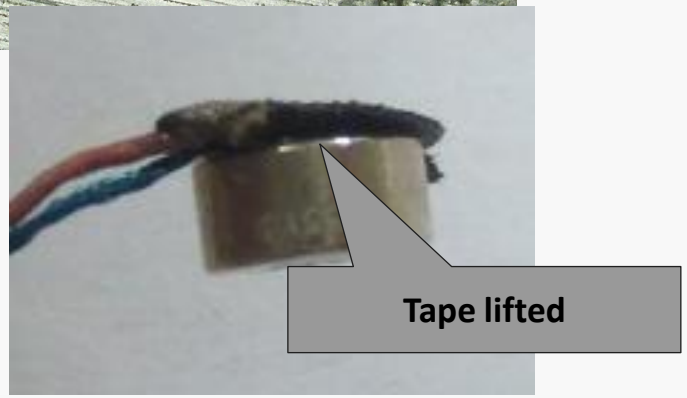
Shield back of microphones with conductive fabric (metal mesh).

Ensure shield is grounded to mic housing with conductive adhesive

Use Kapton tape to prevent shorting of mic solder pads.







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QC Earbuds

Product Overview

True Wireless In-Ear (TWIE) headphones with noise cancellation

First product of this type for Bose

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QC Earbuds - Unexplained Noise Coupling

“Weird Noises” in Some Conference Rooms

Buds were sometimes making tonal, narrowband sounding noises, but only sometimes and in some physical locations

First noticed in a particular conference room

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QC Earbuds - Unexplained Noise Coupling

Some Clues to Root Cause

Frequency and loudness would modulate with movement, head position

Noise would get noticeably louder when standing in certain places

Covering the bud with your hand would stop the noise

Covering just the microphones with a finger would stop the noise

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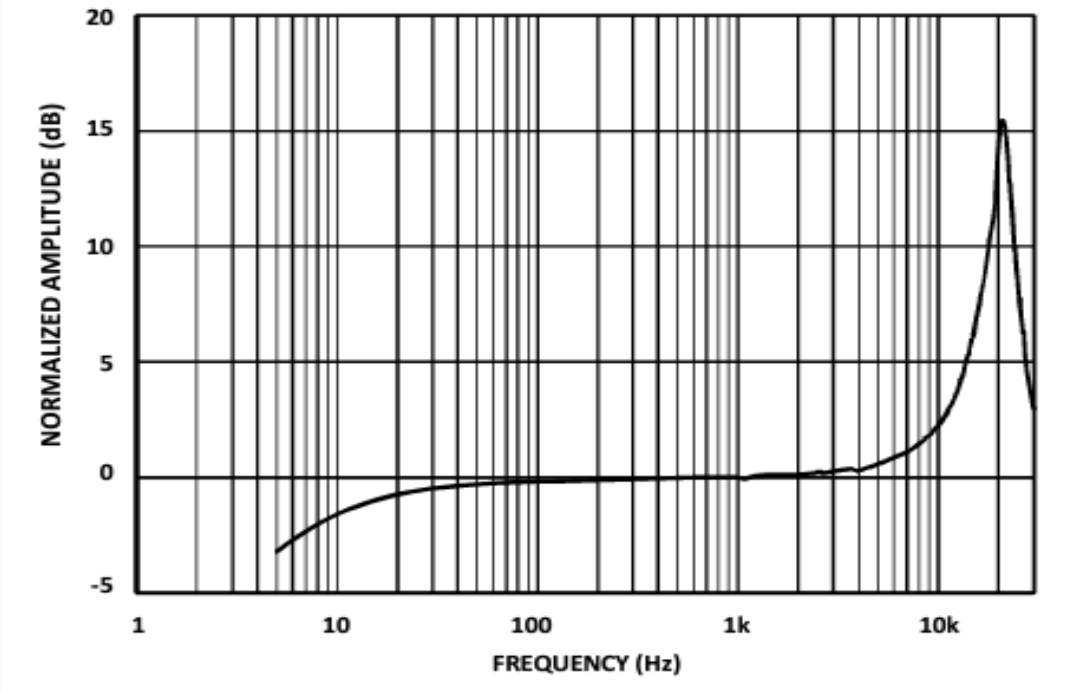
QC Earbuds - Unexplained Noise Coupling

Microphone Frequency Response

This product utilized MEMS microphones

MEMS mics typically have a resonant peak of sensitivity between 20-30kHz

What could excite the microphone in this frequency range?



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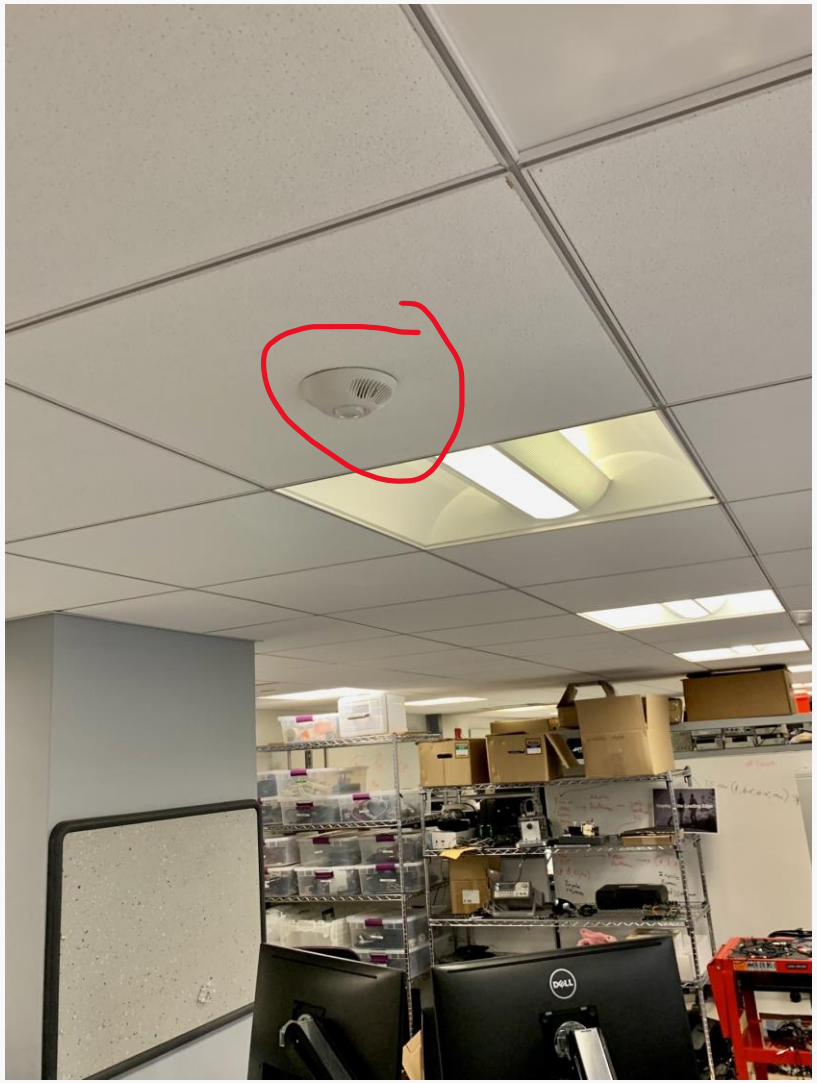
QC Earbuds - Unexplained Noise Coupling

The Answer

Some motion detectors utilize sensors that emit ultrasonic sound energy in the 30-50kHz range.

High output levels are enough to saturate or clip the microphone input, causing unpredictable overload behaviors.



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QC Earbuds - Unexplained Noise Coupling

Outcome

Worked with mic manufacturer to understand root cause and potential fixes.

Root cause: Mic ASIC clock frequency was aligned with ultrasonic output of sensor.
Nonlinear mixing of ultrasonic noise contaminated the internal clock signals.

Clock change proposed to ASIC to move away from ultrasonic frequency peak.

Note: A recurrence of this same problem happened with the next gen product.
Different mic, different root cause, different fix!

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QC Earbuds II

Product Overview

2nd generation TWIE earbuds with noise cancellation

Better performance, smaller form factor

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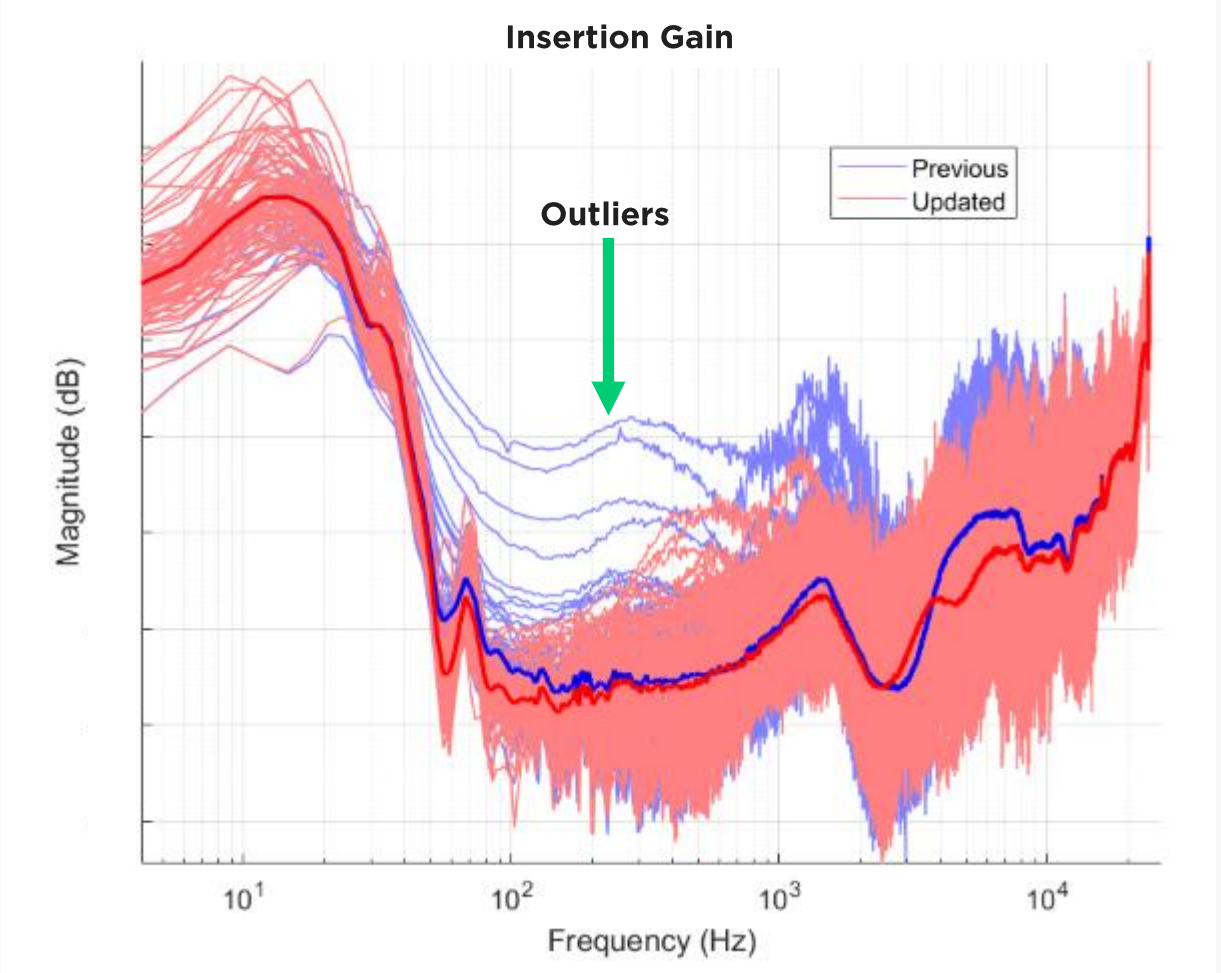
QC Earbuds II – Loss of Noise Cancellation

Problem

For some users, noise reduction performance was degraded

Could be many reasons why this could occur



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QC Earbuds II – Loss of Noise Cancellation

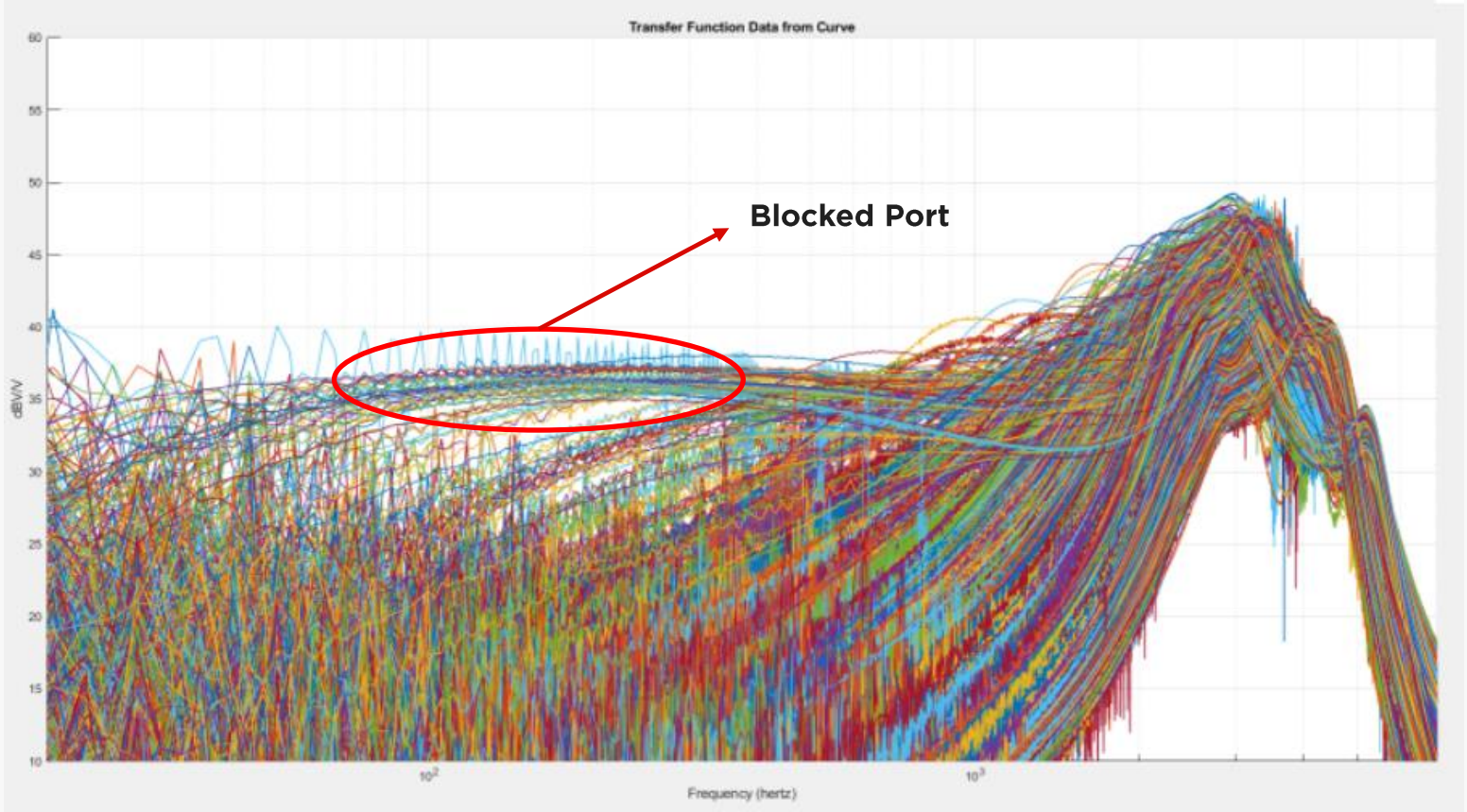
Port Block Experiment

Prototype devised to evaluate potential to block acoustic port

Measurements conducted on large group of human subjects

High output = blocked

Low output = open



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QC Earbuds II – Loss of Noise Cancellation

Solution

Relocate port exit to prevent occlusion

No perfect solution, but had to choose best compromise

Old

New

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Current (Unreleased) Development Product

Product Overview

New headphone using new microprocessor

New processor is variant of part used in existing products – “it should just work”

Product has self test capabilities, can stream PCM digital audio data out via I2S

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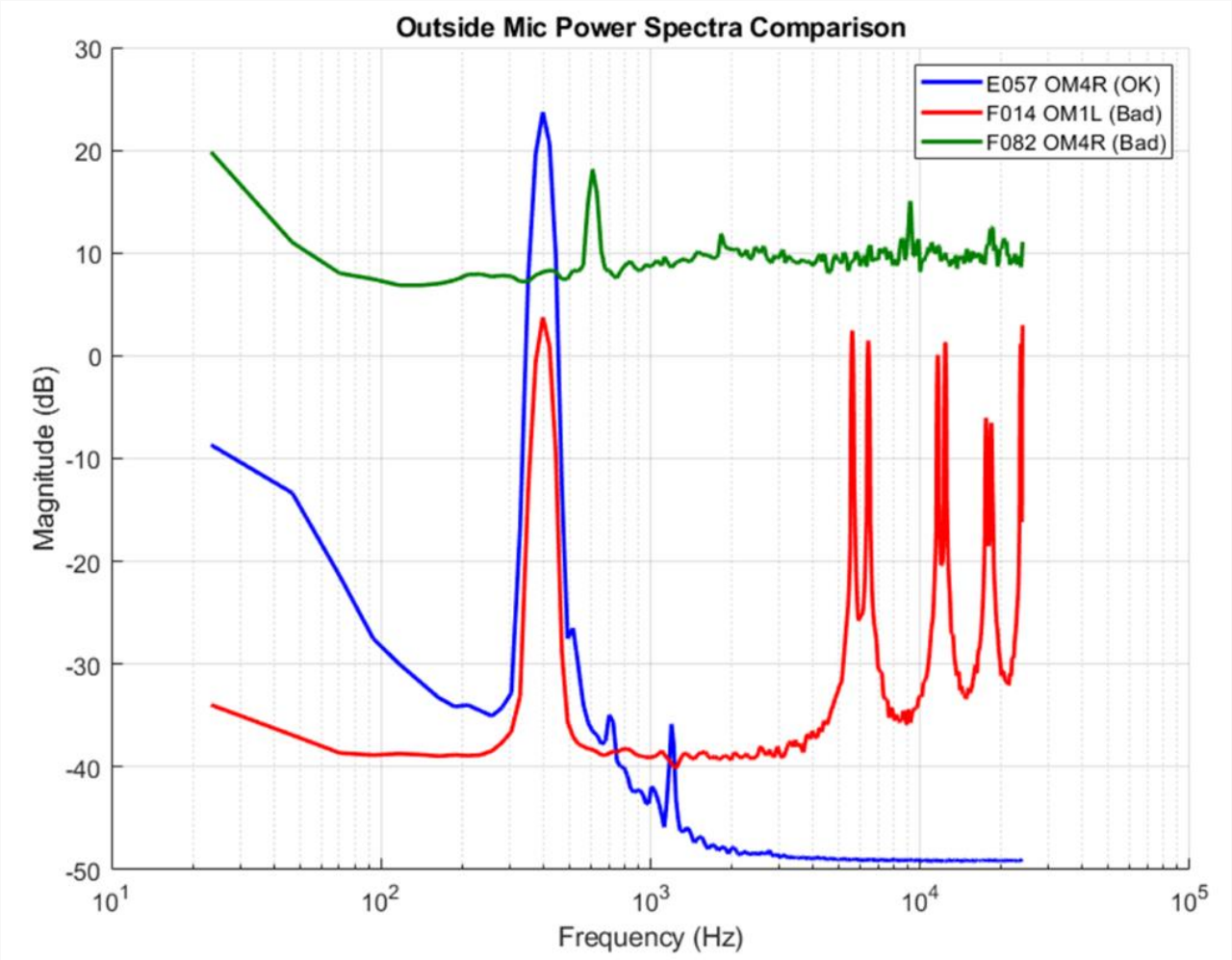
Current (Unreleased) Development Product

Problem

Acoustic calibration response data from I2S was attenuated, and contained high frequency noise on about 40% of units

Acoustic fixture evaluation showed that there was no true acoustic difference. Therefore, the I2S data was incorrect.

But why?



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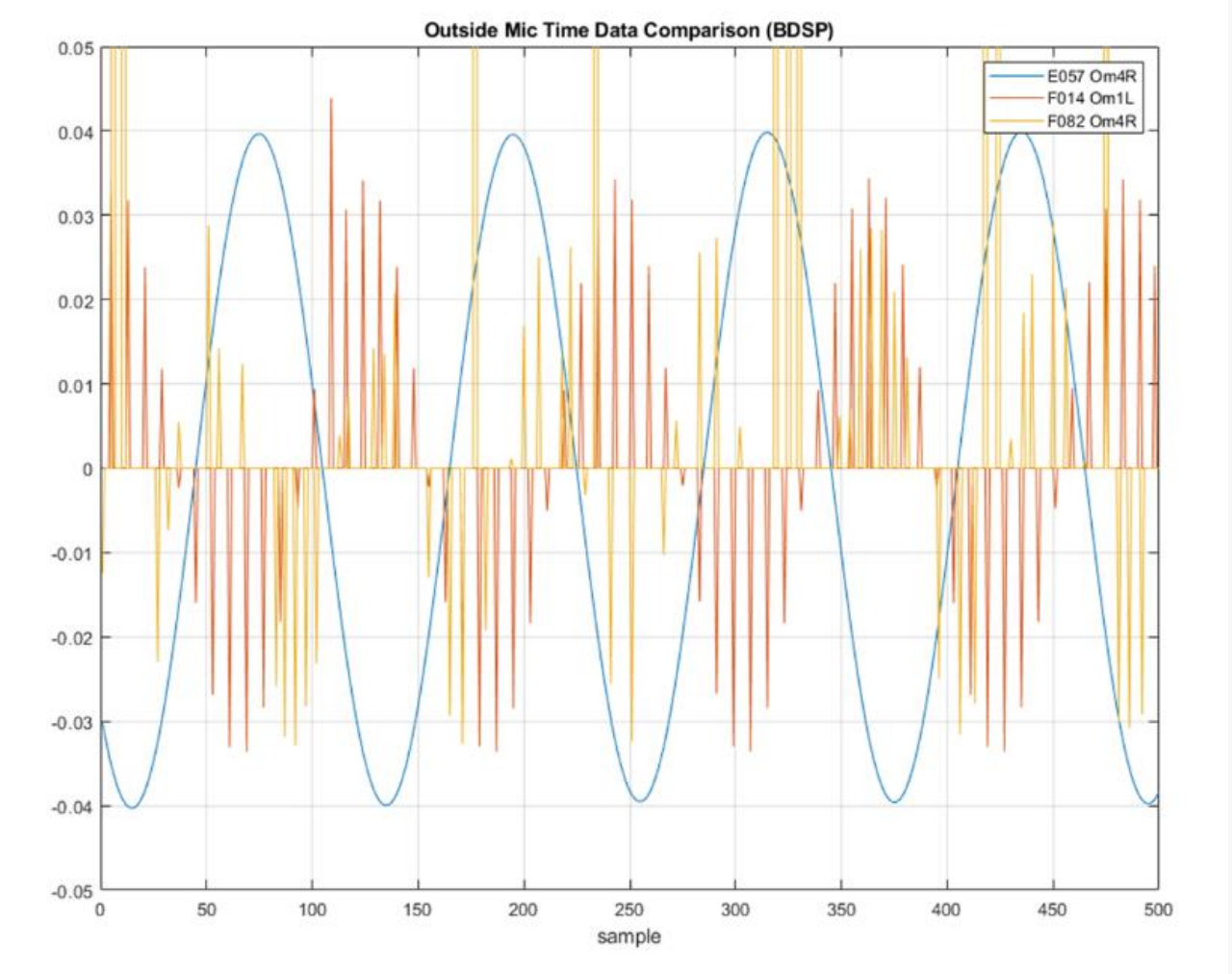
Current (Unreleased) Development Product

Analysis

Check time series data

Noticed many samples were zeroed out on bad units



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Current (Unreleased) Development Product

Analysis

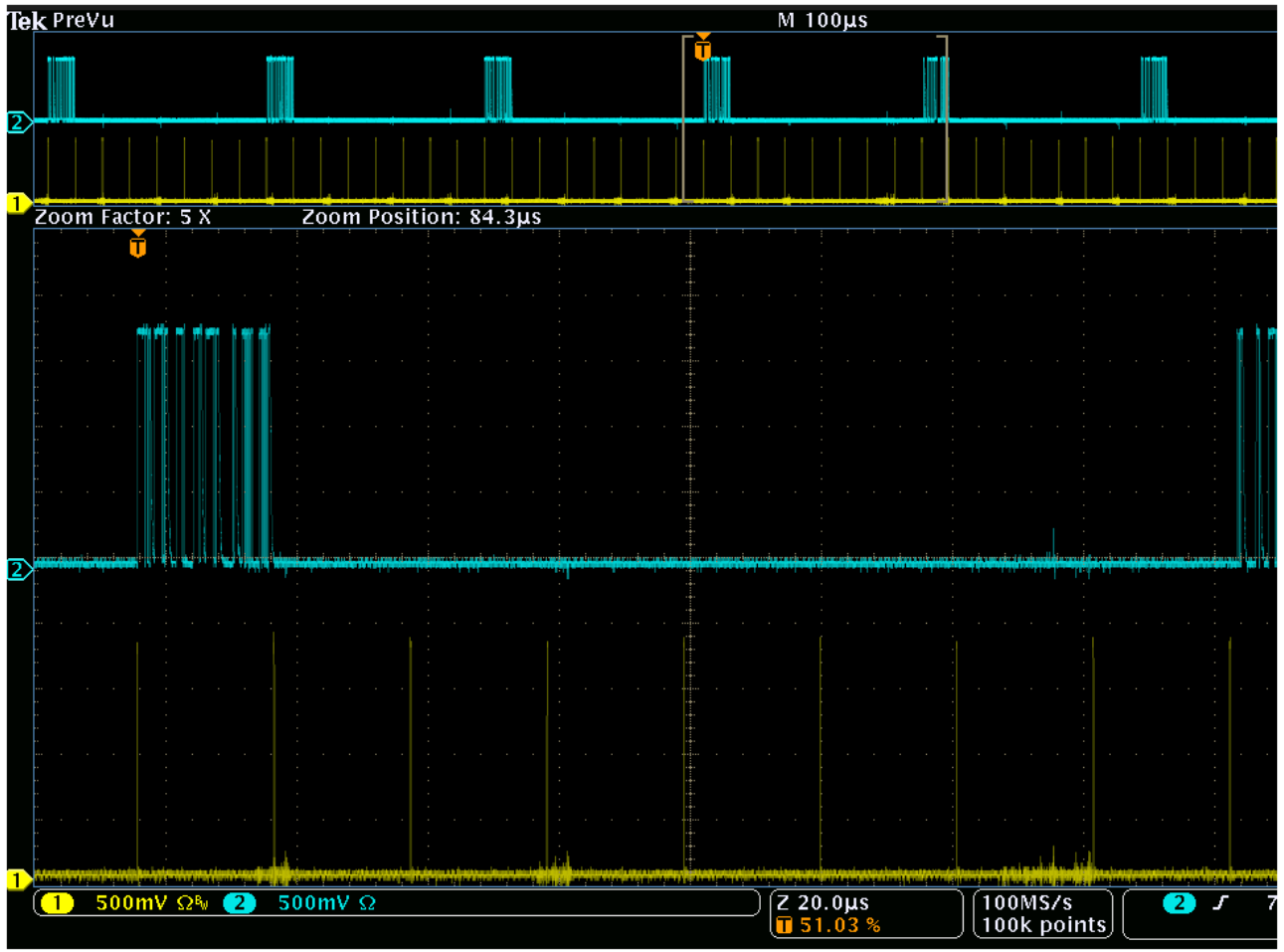
Check digital sample data

Only 1 of every 8 frames contained data

I2S Line (for Measurement Data)

Serial Data

Frame Sync



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Current (Unreleased) Development Product

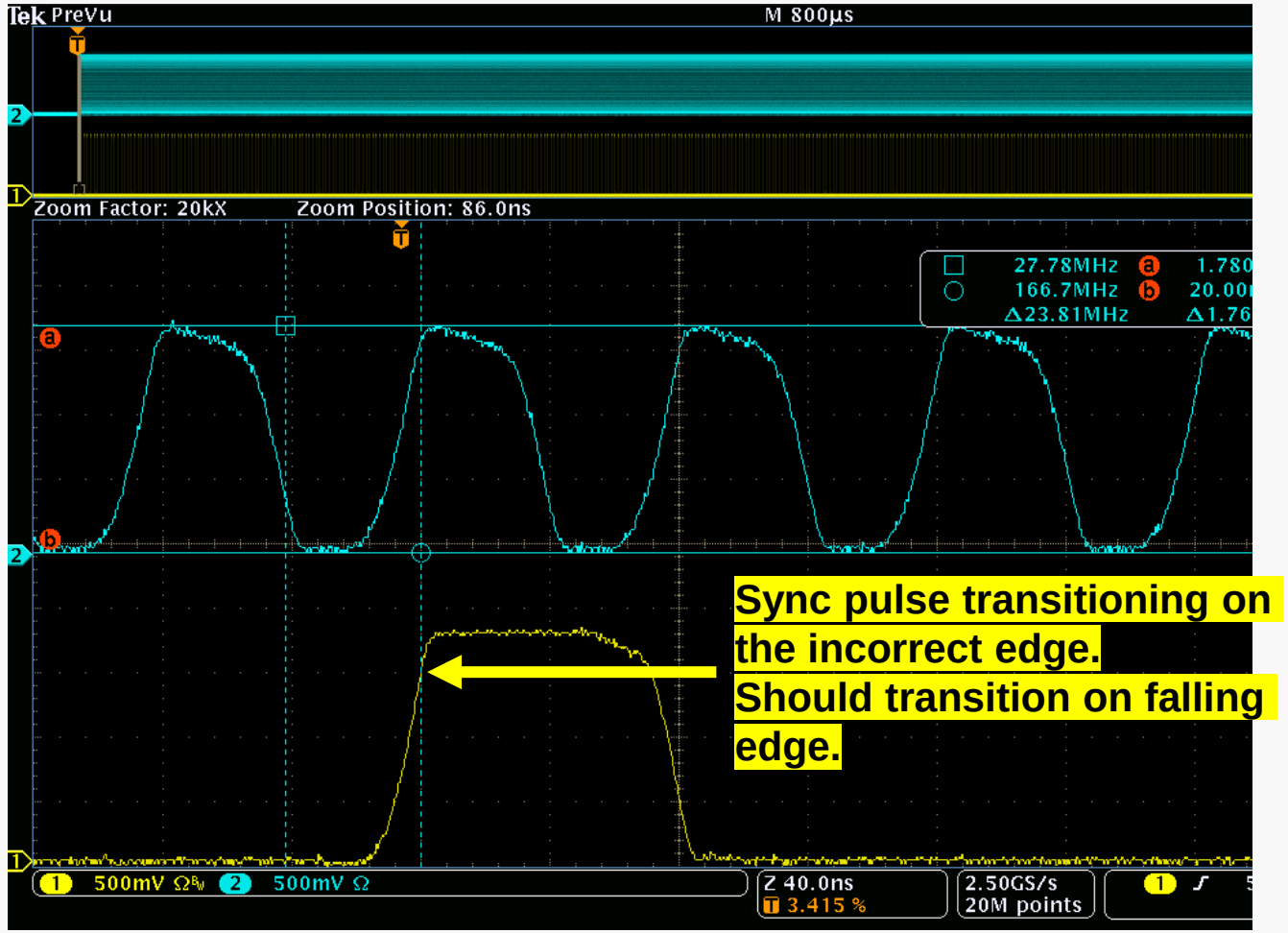
Root Cause and Solution

Frame sync was triggering incorrectly on the rising edge of the clock signal.

Notice the clock signal is not a perfect square wave – this shape is influenced by the variations in passive component values. This explains the unit to unit variation for this issue.

Adjusting the device Firmware setting to trigger on the falling edge restored functionality to all devices.

I2S Line (for Measurement Data)



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Summary of Issues

Many sources of root cause and corrective action

Note that all of these issues have audio performance related symptoms

Product	Issue	Root Cause	Solution Type
OE1	Acoustic mesh too resistive	Material	Process
IE1	Source impedance causes audio performance variation	EE Design	Requirements
IE2	Electric shock to users running on treadmill	Electro-Mechanical	Material
QC20	Tic sound under high driver excursion	Mechanical	Process
QC20	60 Hz hum	EMC	EE Design
QCE1	Ultrasonic noise coupling	Electro-Acoustic	Component
QCE2	Acoustic port blockage	Human Factors	ME Design
Future	Audio data digital communications	Electro-Acoustic	Firmware

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Key Takeaways

Expect and plan for unexpected, discovered work to emerge along the way

Understand: Requirements and use case are the referees keeping you on the field

- Does the problem need to be solved?
- What constitutes a sufficient solution?

Root Cause Analysis can sometimes be tricky

- Cross-functional, system thinking required to identify and solve complex issues

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Key Takeaways

Solutions can come from a variety of places

- Mechanical design
- Components
- Materials
- Manufacturing process
- Firmware
- Requirements change

Tradeoffs between disciplines are inevitable

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