Acoustic Attack Simulation in COMSOL

Thilak Reddy Kanala

1. Introduction

1.1. Introduction and context of the study

As cyber-physical systems become increasingly integrated and data storage transitions to unconventional environments, the susceptibility of critical components, such as hard disks, to acoustic attacks is increasing. This research project aims to simulate and analyze the intricate dynamics of acoustic interference on magnetic hard disk drives (HDDs) deployed in underwater data centers. Leveraging the advanced capabilities of COMSOL Multiphysics, we aim to comprehensively model and simulate diverse acoustic attack scenarios to understand the vulnerabilities and failure modes of HDDs, especially in fluid domain like water.

Recent studies indicate the feasibility of acoustic attacks not only in air but also in water **[1]**. They tackle critical questions surrounding the impact of acoustic interference on HDD operations, drawing insights from extensive research on the topic. This research project builds upon this work by simulating a scenario with HDDs placed under fluid domain and analyzing their mechanical response.

The paper outlines the research questions, objectives, and milestones of the task, providing a roadmap for systematically investigating the effects of acoustic interference. Furthermore, we delve into the background and related work, citing key studies that contribute to our understanding of acoustics in COMSOL and vulnerabilities in HDD structures. The methodology section outlines the techniques employed, emphasizing the use of COMSOL for accurate modeling and simulation.

1.2. Research questions and objectives of the project

The specific effects on hard disk operations in the event of an acoustic interference attack involves potential disruptions to the read/write head, leading to deviations beyond the established working thresholds. The fundamental questions driving this research are to uncover what precisely causes hard disks to fail under the influence of acoustic interference, and secondly, does the identified failure scenario apply uniformly across both air and water mediums?

We hypothesize that the read/write head stands as the most vulnerable component in the face of acoustic interference, likely deviating beyond its operational threshold. The main objective of this project is to substantiate this hypothesis through a comprehensive investigation into the structure and functioning of a typical hard disk, especially in the fluid domain.

To achieve this, the project involves the simulation of acoustic interference attacks on hard disks and data centers. This simulation involved the manipulation of acoustic wave and water parameters to observe their impact. The primary focus will be on understanding the interplay between sound waves, and structural components of hard disks.

1.3. Objectives and milestones of the task

The individual tasks I perform start with performing a comprehensive analysis of the hard disk's structure and working principles. The milestones involve modeling a realistic representation of a hard disk within the COMSOL 3D engine and identifying the components susceptible to acoustic attacks. Utilizing the Acoustic-Solid Interaction (ASI) Physics library in COMSOL to precisely model acoustic wave physics. Accurately simulate how sound waves interact with solid structures within a fluid domain.

Once the model is established, the task involves introducing acoustic interference into the system while considering the additional complexity of a fluid domain, simulating a water environment. The response of various components of the hard disk are observed to identify patterns and potential failure scenarios. Explicitly defined failure scenarios based on previous research are used to observe if these failures are reached under the influence of acoustic interference. This provides a foundation for achieving the objectives of the project.

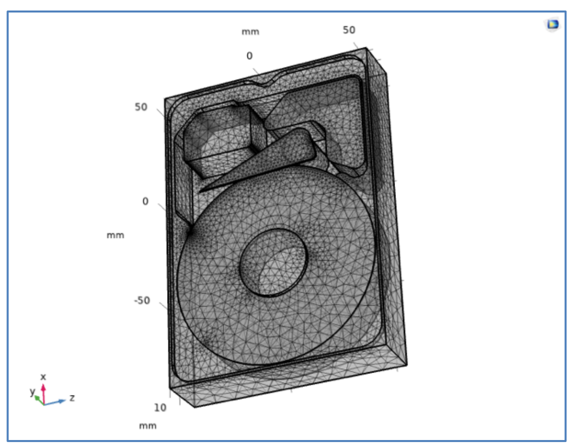

Figure 1: 3D Model of Hard Disk with Mesh

2. Background and related work

2.1. Acoustic Physics in COMSOL

The Acoustic-Solid Interaction (ASI) module in COMSOL Multiphysics facilitates the simulation of the interaction between acoustic waves and solid structures. It is used to quantify the impact of mechanical vibrations induced by acoustic waves on surrounding solids. Leveraging the Frequency Domain Multiphysics interface allows for in-depth analyses in the frequency domain, which we utilize in this project. These tools collectively enable a focused exploration of how specific frequencies impact the interaction between acoustic waves and solid materials.

In recent research **[2]**, **[3]**, **[4]**, the authors used COMSOL Multiphysics to simulate the vibroacoustic response of a hard disk drive (HDD) in various attack scenarios. The Finite Element Model unveiled displacements exceeding operational thresholds, affecting both the disk and read/write head. This utilization of COMSOL contributed significantly to understanding how potent acoustic waves could result in HDD throughput loss, highlighting its effectiveness in analyzing acoustic interference effects on HDD components.

Furthermore, Johnson Controls utilized COMSOL to simulate defense strategies against acoustic attacks on enterprise HDDs, as detailed in **[5]**. Their Acoustic Calculator recommended sound levels below 110 dBZ and suggest strategically placing suppression nozzles for optimal defense. This underscores the practical application of COMSOL in devising effective strategies to mitigate the impact of acoustic interference on critical systems.

2.2. Vulnerability in the structure of a hard disk

In a standard HDD design, a spindle supports flat circular platters crafted from non-magnetic materials like aluminum alloy, glass, or ceramic, housing recorded data. Information is read and written as the platters rotate past read-and-write heads, positioned extremely close to the magnetic surface, with a flying height typically in the range of tens of nanometers. These heads detect and modify the magnetization of the material passing directly beneath them **[6]**.

An acoustic interference attack capitalizes on sound waves inducing mechanical vibrations inside the HDD's case which causes displacement on internal components. When subjected to a specific frequency, resonance is triggered, significantly amplifying the vibration effect. To mitigate potential damage, hard drives automatically stop or reduce read/write operations when a platter vibrates or read/write head is displaced beyond working threshold, preventing the risk of scratching storage disks within the confined spaces where vast amounts of critical information are stored **[7]**.

In a demonstration outlined in **[8],** a researcher showcased the conversion of a hard disk drive (HDD) into a rudimentary microphone by exploiting sound-induced vibrations. This innovative approach sheds light on potential security risks associated with repurposing HDDs for unintended functionalities. Such findings highlight the importance of considering unforeseen vulnerabilities in HDD designs, particularly concerning their susceptibility to acoustic interference.

3. Methodology

COMSOL Multiphysics environment, utilizing the acoustic-structure interaction module is used to closely simulate an approximation of the required setup, where the hard disk is submerged under water. We do not monitor data transfer rates, throughput, or the crash sensor of the hard disk as that requires the hard disk to be booted-up, which cannot be simulated in the COMSOL environment. The metrics described in **Table 1** were used to test the hard disk components under the influence of acoustic pressure.

The model as shown in **Figure 1** intricately replicates a hard disk within a 3D simulation, enclosed by a water sphere. Materials like acrylic plastic and Aluminum 3003-H18 emulate the hard disk case, read/write head, and platters respectively. The simulation captures the behavior of the solid hard disk submerged in water, subjected to an incident acoustic wave. The model calculates the solid's frequency response and feeds this data back to the acoustics domain for a comprehensive analysis of resulting wave patterns.

Name	Expression	Value	Description
F	5000 [Hz]	5000 Hz	Frequency
k1	sin(theta)*cos(phi)	0.75	Incident wave direction vector X
k2	sin(theta)*sin(phi)	-0.43301	Incident wave direction vector Y
k3	cos(theta)	-0.5	Incident wave direction vector Z
phi	(-pi/6) [rad]	-0.5236 rad	Wave direction angle
R	300 [mm]	0.3 m	Fluid Domain Radius
Theta	(4*pi/6) [rad]	2.0944	Wave direction angle

Table 1: Parameters used to generate acoustic wave and fluid domain.

Setting up the model involves using the Acoustic-Solid Interaction, Frequency Domain Multiphysics interface, which integrates Solid Mechanics and Pressure Acoustics, Frequency Domain. It establishes the Acoustic-Structure Boundary Multiphysics coupling for a holistic simulation. Sound wave parameters are defined, and the waves are generated during this simulation.

The incident sound wave interacts with the water sphere, transmitting waves to the hard disk. Coupled by the physics engine, these waves induce noticeable displacements in the hard disk components. The resulting sound pressure interaction is graphically represented in a 3D plot, providing a visual depiction of the displacement occurring across various hard disk components. This simulation with COMSOL serves as a valuable tool in comprehending the dynamics of acoustic interference on underwater hard disk systems.

We define the failure scenario as 5 nm margin for compromising the write operation and 7.5 nm margins for compromising the read operation **[9], [10]**. Another failure scenario is the crash sensor of the hard disk being triggered at ultrasonic frequency acoustic attack, but this cannot be simulated and hence an attack of this nature is not analyzed.

Beyond my task, the tasks assigned to the other members were to simulate various configurations of the data center, modify the properties of the fluid domain and modify the properties of the acoustic wave to observe the variations in the mechanical response of the hard disk under these different conditions. Furthermore, their task involved analyzing the effects of placing a hard disk within different data center shapes which are in turn filled with nitrogen.

The task for varying data center configurations involved conducting simulations to optimize data center design, considering materials such as aluminum 3000 series, aluminum 6000 series, high-strength steel alloy, and plastic. A cylindrical structure measured 40m x 10m with a 0.5m thickness, and a 10x10x40m cuboid was also simulated. Special attention was given to efficient hard disk accommodation with carefully designed shelves. To boost efficiency and environmental sustainability, the datacenter was filled with Nitrogen gas. This decision was motivated from the success of Project Natick, an underwater datacenter using Nitrogen for its inert properties, minimizing interactions with materials **[11]**.

4. Experimental Results

In addressing my specific task, the initiation of an acoustic interference attack was simulated through the utilization of the experimental setup described in the previous section. The objective of this preliminary simulation was to closely analyze behavior exhibited by these components when subjected to acoustic interference. To assess potential failure scenarios, we refer to the thresholds defined in the previous section, displacements of 5 nm for reads and 7.5 nm for writes.

In this initial simulation, conducted at audible frequencies of 5 kHz and 10 Hz, we observed that the read/write head experienced displacement beyond established working thresholds as shown in **Figure 2** and **Figure 3**. This observation indicates the vulnerability of the read/write head to acoustic interference, confirming it as the most susceptible component in the system.

Furthermore, our findings suggest that the effectiveness of an acoustic interference attack remains consistent, whether conducted in water or air. This insight enhances our understanding of the broad-reaching impact of acoustic interference on hard disk components, regardless of the environmental medium. These observations also indicate that there is potential for attacking data centers submerged under water.

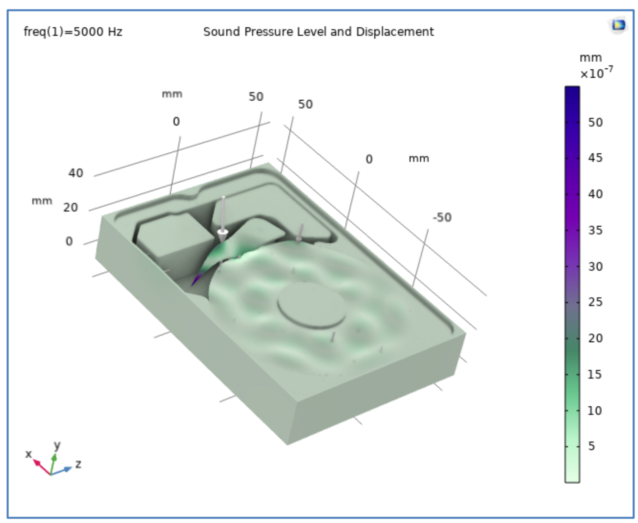

Figure 2: Mechanical response under acoustic interference of frequency 5 kHz

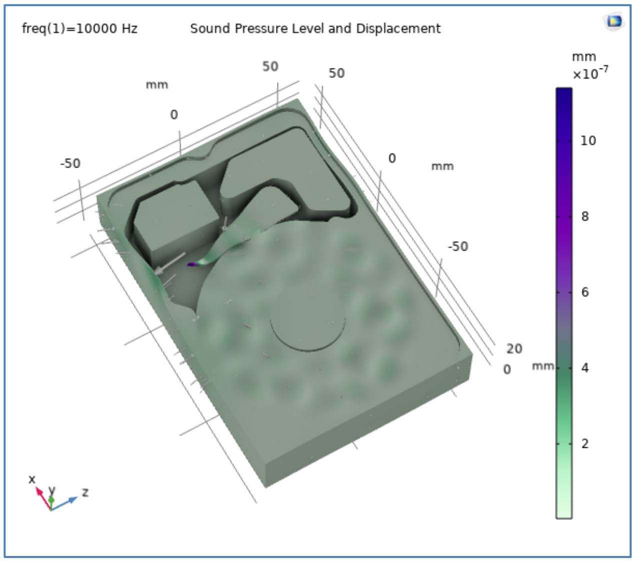

Figure 3: Mechanical response under acoustic interference of frequency 10 kHz

5. Analysis and discussion

5.1. Takeaways

Under diverse acoustic and water parameter scenarios, our observations consistently reveal the vulnerability of the read/write head in hard disks. The displacement beyond working thresholds impedes the operation of the hard disk, impacting both read and write operations.

Highlighting the effectiveness of acoustic attacks in air and water, as demonstrated by previous research, our work extends this understanding by simulating an acoustic attack in water. Our observations confirm that acoustic interference remains a potential attack vector in an underwater environment.

The acoustic-structure interaction physics module in COMSOL, coupled with a precise emulation of a typical hard disk, provide results that are accurate and reliable as they agree with the results of previous research which demonstrates the attack in a real environment. The acoustic displacement 3D graphs offer valuable insights into the critical components of the hard disk, underscoring the vulnerability of the read/write head.

This analysis also highlights the importance of safeguarding the read/write head. Implementation of deviation detection and correction modules, either through software enhancements or embedded within the hard disk itself, could potentially be a vital strategy to protect the device against potential acoustic interference attacks.

5.2. Limitations

Previous research indicates that ultrasonic waves can activate the crash sensor in a hard disk. However, simulating this proved challenging as the crash sensor is a digital component activated during the hard disk's boot-up process.

The propagation of acoustic interference in the hard disk follows a radial pattern, facilitated by the spherical water boundaries carrying vibrations of the acoustic wave to its components. A more precise simulation could involve positioning a loudspeaker at a specific distance and angle from the hard disk to generate concentrated acoustic interference.

Optimizing the attack's intensity by targeting resonant frequencies of the hard disk components could simulate a more realistic scenario. Though not explored in this analysis, such an investigation would be ideal to gain better understanding of mechanical response under resonance.

Enhancing the accuracy of the hard disk model in future research could capture all component interactions, elevating the overall resolution of the simulation. This presents an opportunity for more comprehensive and nuanced exploration in subsequent studies.

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